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STATIC FEED WATER ELECTROLYSIS MODULE

FINAL REPORT

by

J. D. Powell, F.H. Schubert
and F.C. Jensen

November, 1974

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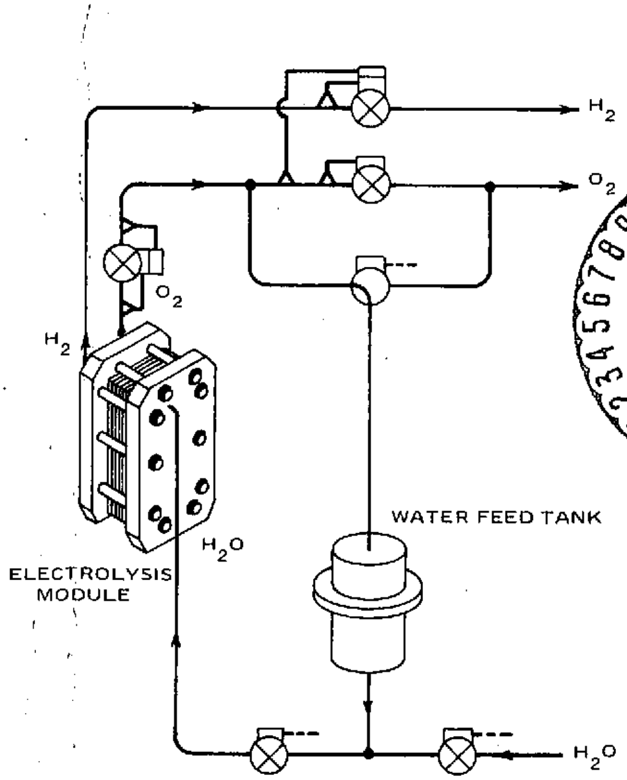
STATIC FEED WATER ELECTROLYSIS CONCEPT



Prepared Under Contract No. NAS 2-7470

by

Life Systems, Inc.
Cleveland, Ohio 44122

for

AMES RESEARCH CENTER
National Aeronautics & Space Administration

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FOREWORD

The development work described herein was conducted by Life Systems, Inc. during the period March, 1973 through November, 1974 under NASA Contract NAS2-7470. The Program Manager was J. D. Powell. Technical support was provided as follows:

Personnel	Area(s) of Responsibility
Fred C. Jensen	Module designs
Franz H. Schubert	System analysis and module design concepts
Jon J. Schneider	Ground Support Accessories design
J. David Powell	Control and monitor concepts and designs
Mike L. Kruszynski	Ground support accessories layout and fabrication and module testing
Glenn A. Little	Single cell testing
Richard A. Wynveen, PhD.	Electrochemical and system analyses

The contract's Technical Monitor was P. D. Quattrone, Chief, Environmental Control Research Branch, NASA Ames Research Center, Moffett Field, California.

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SUMMARY

A program was successfully completed that resulted in the development of a Static Feed Water Electrolysis Module (SFWEM). During a 94-day endurance test the SFWEM demonstrated feed water cavity degassing was no longer needed. The module was designed to generate 0.907 kg/d (2.0 lb/day) of oxygen (O_2) at an operating pressure and temperature of 1724 kN/m^2 (250 psia) and 352K (175F), respectively. The module used an alkaline electrolyte (potassium hydroxide (KOH)) supported in a customized porous asbestos matrix. Feed water was statically added to the module using a pressure referenced accumulator. Water feed to the electrolysis site in each cell was added by water vapor diffusing through the hydrogen (H_2) cavity and into the electrolyte within the porous electrode. Waste heat generated by the electrochemical reactions was removed by circulating water through a coolant cavity in each cell. The cell active area was 92.9 cm^2 (0.1 ft^2). The "cell density" of the module was reflected by three cells per 2.54 cm (1 in). The SFWEM consisted of six cells plus two endplates to support the cells.

Control and monitor instrumentation for the SFWEM was designed, fabricated, and used to operate the SFWEM as a self-contained subsystem with automatic start, stop, and monitoring features for ease of operation and protection of equipment and personnel. The test system was capable of pressure control from 103 to 2758 kN/m^2 (15 to 400 psia), temperature control from 297 to 377K (75 to 220F), and current control from 0 to 50 amps (0 to 538 mA/cm^2 (500 ASF)) at voltages from 0 to 20 volts.

Design and fabrication techniques were arrived at after completing four studies. The designs of the SFWEM and its test system were based on a literature survey of water electrolysis modules' and systems' problems. The problems identified and eliminated were (1) the need for feed cavity degassing, (2) the need for condenser/separators, (3) lack of instrumentation for protection, (4) lack of positive module temperature control, (5) lack of automatic one-button start/stop control, and (6) circulation of bulk electrolyte. The second study examined the maintainability aspects of water electrolysis modules. An insitu submodule maintenance approach was selected and the SFWEM designed to be compatible with this approach. The third study evaluated the applicable heat removal techniques. An internal liquid-cooled method was selected because it offered the lowest equivalent weight. The fourth study evaluated injection molding and machining as fabrication techniques for polysulfone cell parts. The selection criteria used were cost and performance. Injection molding was selected because it offered advantages in both areas.

A static feed water electrolysis test program was successfully completed. This program consisted of (1) test system checkout tests, (2) single cell Design Verification Tests (DVTs), (3) module DVT and parametric tests, (4) module endurance test, and (5) single cell advanced electrode and matrix evaluation tests.

A single cell using SFWEM components was successfully tested for design verification of the SFWEM. These tests included (1) current densities from 0 to 1076

mA/cm^2 (1000 ASF) which verified the electrical design (low IR losses) and electrochemical design (able to sustain high current density operation) and (2) pressures from ambient to 1724 kN/m^2 (250 psia) which verified the mechanical structure and electrical contact designs.

Parametric testing of the SFWEM demonstrated cell performance of 1.78 volts at 538 mA/cm^2 (500 ASF) and 366K (200F). Cyclic on-off operation for five days resulted in improved performance of 20 mV per cell. Additional parametric tests covered operating pressure up to 1724 kN/m^2 (250 psia), and process fluid differential pressures from -34 kN/m^2 to +34 kN/m^2 (-5 psid to +5 psid).

An endurance test which lasted 94 days (2256 hours) was successfully completed on the SFWEM. A total test time of 111 days (2664 hours) were accumulated on the SFWEM including shakedown and parametric tests. The endurance test demonstrated that the SFWEM design has eliminated feed water cavity degassing requirements by operating for 440 hours at 1724 kN/m^2 (250 psia) and 488 hours at 807 kN/m^2 (117 psia) without gas accumulation or cavity venting. The remaining 1328 hours were devoted to identifying operating conditions at which cavity venting begins.

Short-term tests were performed on a single cell at ambient pressure and a 327K (130F) temperature which identified an electrode with better performance (34 mV lower internal resistence free voltage at 215 mA/cm^2 (200 ASF) and a matrix which has better performance (58 mV lower terminal voltage at 215 mA/cm^2 (200 ASF), and has better high temperature capabilities. Endurance testing of the high performance electrode and high temperature testing of the new matrix is now required.

A Dehumidifier Module (DM) was successfully designed, fabricated, and tested. The module removed the moisture from the SFWEM product gas streams by absorbing it into sulfuric acid (H_2SO_4) electrolyte and subsequently electrolyzing it. This eliminates the need for subsystem condensor/separators and produces additional O_2 and H_2. The module design was similar to the SFWEM except (1) the water feed cavity was eliminated, (2) there were only three cells, (3) it was designed to run at lower current densities (54 mA/cm^2 (50 ASF) maximum), and (4) it used acid-compatible materials. The DM accepted the total SFWEM O_2 and H_2 flows and reduced their dew points to 287K (57F) or below.

The DM test system was designed, fabricated, and successfully used to operate the DM. A limited characterization test was completed which demonstrated the performances exceeded the design goal of 1.90V per cell by 0.2V per cell, indicating fewer than the three cells per one man O_2 capacity SFWEM would be needed.

INTRODUCTION

Technology and equipment are needed to sustan man in space for extended time periods. The objective of this program was to develop an advanced Static Feed Water Electrolysis Module (SFWEM) and associated instrumentation to generate breathable oxygen (O_2) through the electrolysis of water with the byproduct hydrogen (H_2) available for use in an Air Revitalization System (ARS) for the recovery of O_2 from metabolic carbon dioxide (CO_2).

Background

Past development efforts on water electrolysis systems and modules employing the static water feed concept have demonstrated this system's inherent simplicity and long operating life capabilities.(1-5) Various approaches to system design by different developers(6-8) and results of extensive test programs have identified potential improvements and problems to be avoided in the design of a Static Feed Water Electrolysis System (SFWES)(5) and of water electrolysis systems in general.(3)

The major problems identified with the SFWES were: (1) the need for feed water degassing, (2) the need for condenser/separators, and (3) the need for high cell voltages to sustain high current densities.

Program Objectives

The overall program objective was to develop a SFWEM and associated test system which would avoid the problems and design limitations and make the SFWES concept a viable candidate for spacecraft application.

To accomplish this the program's efforts were directed towards meeting four specific objectives:

1. Elimination of water feed compartment degassing.

2. Elimination of the need for zero gravity condenser/separators through the use of product gas decompression and electrochemical dehumidification.

3. Increase current density capability through increasing electrode performance and optimizing cell configuration.

4. Emphasize "self-contained" aspects during the module's testing so that operation is independent of laboratory instrumentation and complicated startup/shutdown procedures.

General objectives considered throughout the program were:

1. Advancement of water electrolysis technology as far as possible without risking the design on such an advanced concept that might prevent successful completion of the Parametric Test Program.

2. Aim toward a flight-qualifiable configuration with the technology program not viewed as an isolated end in itself, but as a step toward designing the optimum method for meeting the water electrolysis requirements of future space activities.

3. Development of a module (O_2 and H_2 generator) with the best chance for incorporation into the Space Station application when integrated with the normal subsystem accessories. The Space Station Prototype's (SSP)(9) applicable design specifications were used as a guide throughout the development as well as the results of NASA's Modular Space Station studies.(10)

Program Organization

To accomplish these objectives the program was divided into four tasks:

Task	Description
1.0	Design, fabricate, and assemble the SFWEM, water supply, and DM
2.0	Design, fabricate, and assemble the SFWEM and DM test systems
3.0	Single cell and module testing
4.0	Program management and data requirements

STATIC FEED WATER ELECTROLYSIS MODULE

The design of the SFWEM was based on the specifications set forth in the Statement of Work (SOW) and the background knowledge that the Contractor possessed in the area of static water feed, in particular, and water electrolysis in general.

Major emphasis was placed on using design concepts that allowed module operation at conditions resulting in the elimination of condenser/separators in the module's product gas lines and elimination of the need for water feed compartment degassing.

Design Specifications

The detailed design specifications to which the SFWEM was designed are listed in Table 1. The accepted figure for man's metabolic oxygen (O_2) requirement of 0.835 kg/d (1.84 lb/day) falls within the O_2 generation rate specified for the SFWEM. The capacity of the module was, therefore, sufficient for a one-man O_2 generation system.

The increased operating pressure range was selected to allow operation without feed water degassing and without condenser/separators. The specified performance of 1.7 volts at 107.6 mA/cm^2 (100 ASF) and 1.9 volts at 215.2 mA/cm^2 (200 ASF) had been demonstrated with modules in short-term operation at pressures less than 689 kN/m^2 (100 psia). The voltage performance goal at elevated pressures and for long operating durations presented a challenge.

Electrolysis Design Concepts

The design of any water electrolysis module requires the definition of four basic concepts. They are:

1. Electrolyte (acid or alkaline).

2. Electrolyte incorporation.

3. Water feed.

4. Heat removal.

TABLE 1 SFWEM DESIGN SPECIFICATIONS

Oxygen Generation Rate, kg/d (Lb/Day)	0.680 to 0.907 (1.5 to 2.0)
Operating Pressure Range, kN/m^2 (Psia)	103 to 1724 (15 to 250)
Operating Temperature Range, K (F)	Ambient to 366 (200)
O_2 to H_2 Pressure Differential (Max), kN/m^2 (Psid)	34 (5)
H_2 to Water Pressure Differential (Max), kN/m^2 (Psid)	34 (5)
Active Cell Area Range, cm^2 (Ft^2)	92.9 to 185.8 (0.1 to 0.2)
Cells per cm (In) (Min)	1.18 (3)
Matrix Thickness (Max), cm (In)	0.076 (0.030)
Performance, V	
At 108 mA/cm^2 (100 ASF)	1.7
At 200 mA/cm^2 (200 ASF)	1.9
Water Feed Mechanism	Static
Gravity, G	0 to 1
Duty Cycle	Continuous and Cyclic

Electrolyte

An alkaline electrolyte was selected for the SFWEM because materials problems and power requirements are less than with comparable acid systems. An aqueous solution of potassium hydroxide (KOH) was selected because of its high conductivity and water vapor pressure depressant characteristics. The concentration at which the module was charged was selected to provide an optimum compromise among the factors of water vapor contained in the product gases, electrolyte conductivity needed for efficient high current density operation without electrolyte precipitation and minimization of the dissolution of gases from the feed water.

Electrolyte Incorporation

The electrolyte was incorporated in a porous matrix made from custom-blended matrix material to:

1. Avoid quantities of bulk electrolyte within the system for increased safety and lower equivalent weight.

2. Avoid the need for an electrolyte circulating pump.

3. Keep the feed water separated from the cell electrolyte and electrodes for increased operating life by avoiding contamination due to possible impurities contained in the feed water.

4. Keep the cell electrodes close together for low internal resistance, hence low equivalent weight.

5. Provide a higher stability to pressure differentials impossible with standard fuel cell asbestos matrices.

Water Feed

The SFWEM uses a static water addition concept. This method of water addition is preferred because it is simple, reliable and minimizes subsystem components and controls. It enables keeping the feed water separated from the cell electrolyte and minimizes the amount of bulk liquid electrolyte present in a water electrolysis system. This concept also provides for a way of avoiding aerosol formation by allowing accurate control of the cell's moisture level.

Heat Removal

A liquid coolant loop circulating through separate cooling compartments within each cell of the SFWEM was selected to remove the waste heat generated by the electrochemical reaction. Past static feed systems have used evaporative cooling concepts or aircooled external fins. Evaporative cooling techniques prevented positive module temperature control while also being incompatible with high pressure operation. Modules cooled with ambient air are simple in construction, but are generally bigger and heavier and have current density limitations due to increased thermal gradients.

Specifically, the liquid coolant technique was selected for the SFWEM because of the following advantages:

1. Capability to operate at high current densities due to lower concentration gradients within the cell matrix based on the smaller temperature differentials across the cell's active electrode-matrix surface.

2. Low equivalent weight due to the lower heat rejection penalties associated with rejecting waste heat to the spacecraft's liquid coolant system rather than ambient air. Previous studies[4] have shown this to become significant at cell voltages greater than 1.75 volts (as resulting from high current densities).

3. Elimination for need of backup cooling methods to protect against cabin decompression, i.e., total lack or reduced availability of cooling air.

4. Lower system volume due to the elimination of the external fins, module cooling shrouds and associated air distribution plenums and ducting (liquid lines and connections are smaller).

5. Lower module weight due to the elimination of metallic external fins and decreased thickness in metallic current collectors dictated by electrical rather than thermal conduction. This is especially true since nickel-plating of high conductivity copper current collector/fins used on past static feed water electrolysis modules is considered undesirable for spacecraft application. A nickel current collector/fin for air cooling would require four times the thickness of an already heavy nickel-plated type for equal temperature gradients.

6. Increased module performance, i.e., lower voltages, hence lower power requirement for a given current density due to uniformity in and optimization of cell electrolyte concentration.

7. Reduced noise levels since liquid prime movers have, in general, lower noise levels than open loop air prime movers.

Process Descriptions

Basically, two major processes occur within a SFWEM. The first is the electrochemical process of water electrolysis in an alkaline electrolyte while the second process is the static addition of water to the module and diffusion to the electrolysis site.

Electrochemical Process

The electrochemical process of water electrolysis occurs within the cell's anode-cell matrix-cathode composite assembly.

The reaction occurring at the anode and cathode of the electrolysis cell with an alkaline electrolyte are:

Cathode

$$2e^- + 2H_2O = H_2 + OH^- \qquad (1)$$

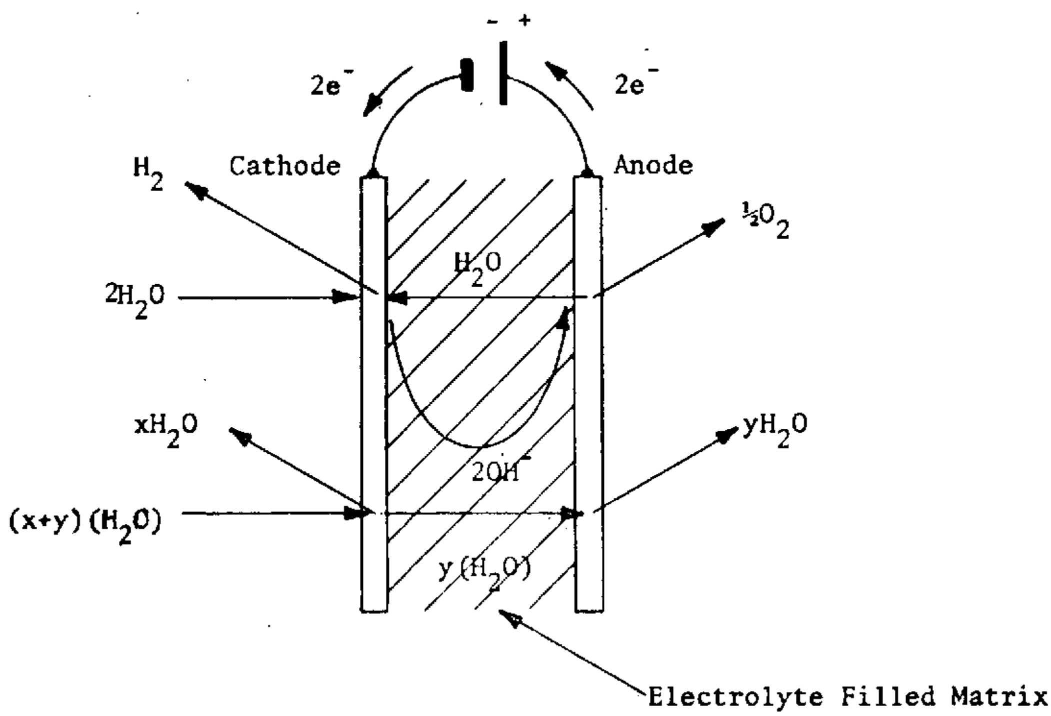
Anode

$$2OH^- = H_2O + 1/2\ O_2 + 2_e^- \qquad (2)$$

resulting in the overall net reaction of

$$\text{electrical energy} + H_2O = H_2 + 1/2\ O_2 + \text{heat} \qquad (3)$$

Schematically, these reactions are shown on the diagram below. The water to be electrolyzed is supplied via the cathode side of the cell. The water components $(x + y)(H_2O)$ not included in the electrochemical reaction represent the water required for humidification of the cathode and anode gases at the pressure, temperature and local concentration of the aqueous electrolyte at the electrodes.



The reactions show that an electrolyte concentration gradient must exist due to the production of water at the anode and consumption at the cathode. The magnitude of this gradient is a function of the characteristics and configuration of the electrodes and cell matrix and the current density. For calculations of humidification requirements the equivalent concentrations of the electrolyte at the respective cell electrode must be used which differ both from the initial charge concentration and from anode to cathode side.

Static Water Feed Process

The static water feed process employed in the SFWEM uses water both in liquid and in vapor form. Liquid static water feed is used from an external reservoir into the individual water cavities of the module's cells. Static water vapor feed occurs from these individual water feed cavities, across the hydrogen (H_2) cavity, to the electrolysis site.

Figure 1 is a functional schematic of a cell designed for the SFWEM. The overall static water feed concept operates as follows. Initially, the water feed cavity, the water feed matrix and the cell matrixelectrodes contain an aqueous solution of KOH electrolyte at equal concentrations. Both the H_2 and O_2 cavities are void of liquid. An equilibrium condition exists prior to start of electrolysis. When power is applied to the electrodes, water from the cell electrolyte is decomposed. As a result, the concentration of the cell electrolyte increases and, therefore, its water vapor pressure decreases to a level below that of the feed compartment electrolyte. This water vapor pressure differential is a driving force causing water vapor to diffuse from the liquid gas interface within the water feed matrix, through the H_2 cavity and cathode electrode into the cell electrolyte. This process establishes a new equilibrium condition based on the water requirements for electrolysis and humidification of the product gases and continues as long as electrical power is applied to the cell electrodes.

As water diffuses from the feed matrix and is removed from the water feed compartment, it is statically replenished from an external source to maintain a constant pressure, volume and electrolyte concentration within the feed compartment. Upon interruption of electrical power, water vapor will continue to diffuse across the H_2 compartment until the electrolyte concentration in the cell matrix is equal to that of the water feed matrix and compartment. At this point, the original equilibrium condition is regained with the electrolyte retained in the cell matrix and electrodes equal to the initial charge volume and concentration.

The increase in the concentration of the electrolyte in the cell matrix during electrolysis is, of course, accompanied by an electrolyte volume decrease, since only a fixed amount of salt is present from the initial charge. This volumetric decrease is a direct function of current density and resistance to water transport from the water feed cavity to the cell electrolyte.

The cell must therefore be designed to prevent electrolyte volume decrease to the point where gas crossover or precipitation occurs. Some of the major considerations to lessen the effect of electrolyte volume decrease are:

1. Optimum initial electrolyte concentration.

2. High electrode-to-matrix thickness ratio.

3. Low resistance to water vapor diffusion across the H_2 compartment.

4. Low resistance to electrolyte and water diffusion within the water feed compartment and water feed matrix.

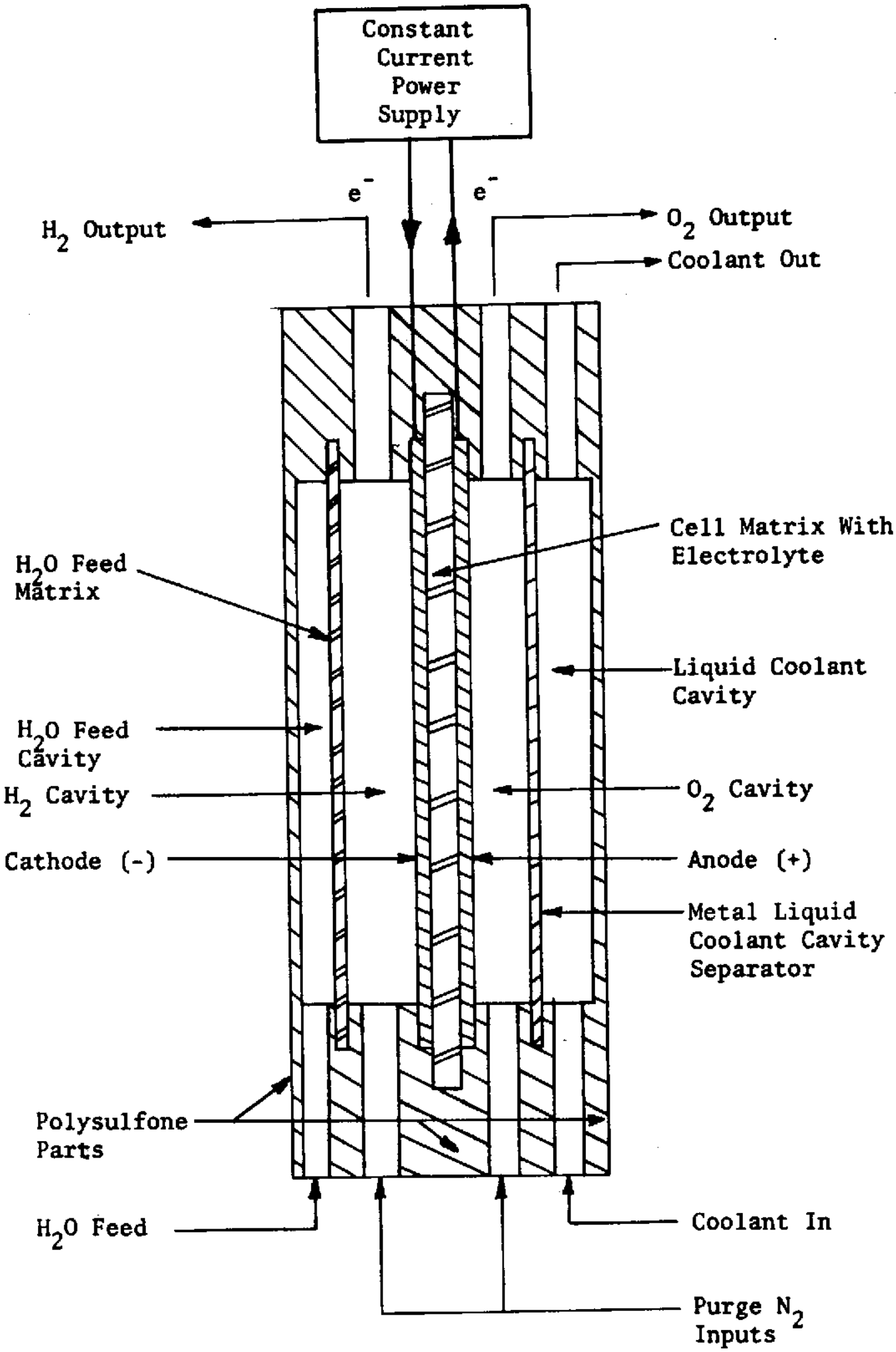


FIGURE 1 FUNCTIONAL SCHEMATIC SFWEM CELL

Electrolysis Problems To Be Avoided

A review of applicable electrolysis literature was performed as part of the design activities of the SFWEM to identify limitations and problems to be avoided. Problem areas identified were either applicable to electrolysis systems in general, or were oriented specifically toward the static feed concept. The SFWEM and its test system were designed with emphasis on avoiding these problems and limitations.

General Water Electrolysis Subsystem Problems

Based on a review of various approaches to water electrolysis subsystems, the following problem areas and limitations were identified.[3,5]

1. Water vapor condensers, associated zero gravity liquid-gas separators, condensed water accumulators and water vent and aerosol traps were sources of increased maintenance, contributed to decreased reliability, and added to subsystem weight and development costs.

2. High liquid volume, zero gravity liquid-gas separators decreased system reliability, and increased subsystem maintenance and development costs.

3. High failure rates of water electrolysis subsystems resulted from failures in peripheral subsystem components rather than in the electrolysis module itself. This resulted in a low mean-time-between-failure and decreased the life of the modules.

4. Lack of automatic startup and shutdown modes caused operator errors and subsequent system failures.

5. Lack of automatic system monitoring and use of performance trend analysis and fault isolation caused less safe conditions for both equipment and personnel.

6. Lack of positive module temperature control resulted in limitations in operation at off-design conditions and in adverse effects on system operation due to environmental temperature changes.

7. Lack of automatic protection against both high and low individual cell voltages resulted in damage to equipment.

8. Operation at low pressure levels resulted in increased aerosol formation, presenting both a module self-destruct mechanism and corrosion potential.

9. Lack of uniform and positive thermal control of individual cells and modules resulted in limited current density ranges and off-design condition operation.

10. Insufficient attention to minimize intra-cell electrical resistance (IR) losses resulted in high power requirements per pound of O_2 generated.

11. Circulation of bulk liquid electrolyte increased the frequency and probability of electrolyte leakage causing safety and maintenance problems.

Static Feed Water Electrolysis Module Problems

Based on the literature survey and on the Contractor's background experience, the following problems were identified as being unique to static feed water electrolysis modules and subsystems.

1. The need for degassing of the feed water or the cell feed water cavities contributed to system complexity and maintenance procedures unique to the static feed approach.

2. The addition of a loop to circulate the liquid contained in the feed water cavities for either temperature control or feed water compartment degassing contributed to module and subsystem problems. These problems resulted from using one single manifold common to both the water feed and the electrolyte circulation inlet port. As a result, electrolyte concentration shifts and concentration buildup in feed cavities occurred. Also, the presence of the metallic recirculation loop plumbing in contact with the KOH caused stray electrolysis i.e., an increase in gas levels in the feed cavities.

3. Liquid purging ports and manifolds in the modules were improperly sized resulting in high pressure differentials through the feed water cavities during flushing. This upset the module pressure differentials and resulted in electrolyte maldistributions and H_2 gas to feed water cavity breakthrough.[6-8]

4. Retention of the water feed matrix between perforated plastic support sheets introduced an extremely high diffusion resistance to KOH and water to and from the evaporation site in the feed matrix. The resulting high electrolyte concentration levels caused cell dryout and limited high current density operation.[6-8]

5. Structural blockage and reduction of the cross-sectional area for water vapor diffusion from the feed matrix to the electrolysis site resulted in high cell matrix electrolyte concentration accompanied by large decreases in electrolyte volume with eventual cell dryout and gas crossovers.[6-8]

6. Water feed manifolds common to all cells in a module were located at the bottom of the module which caused uneven electrolyte concentration shifts in the feed compartments during water feed. These shifts were caused by the difference in electrolyte and feed water densities.

7. Large H_2 compartment thickness increased the water vapor diffusion path length, hence the diffusion resistance of water vapor from the feed matrix to the cell matrix.

8. Inadequate isolation of all metallic parts from the aqueous electrolyte contributed to gassing problems through stray electrolysis.[7]

9. Introduction of individual cell heaters to force an increase in water distillation rate decreased overall system efficiency and presented sources for potential stray electrolysis and cell frame failures.[6,8]

10. Unitized cell construction (bonded successive plastic frames) exhibited short operating life (leakage through the bonded surfaces at the end of a six-month test program).[6,8]

11. Electrolyte bridging between cell and feed matrices due to improper pressure differentials between the H_2 and the feed water resulted in increased potential for stray electrolysis, decrease in current efficiency and maldistribution of electrolyte.[6-8]

12. Improper matrix thickness selection to provide for an adequate electrode-to-cell-matrix thickness ratio limited current density ranges.[6-8]

Elimination of Condenser/Separators

The SFWEM was designed to operate at conditions that minimized the water vapor content in the product gases. To eliminate the need for condenser/separators, the gases must be delivered from the SFWES at a dew point below 287K (57F), typically considered maximum for a spacecraft atmosphere.

The dew points of the product exhaust gases are determined by the water vapor pressure in the gases. A dew point of 287K (57F), for example, corresponds to a water vapor pressure of 1.60 kN/m^2 (12 mm Hg). This partial water vapor pressure level could be attained directly within the module itself, but would mean operation at the very low temperature of 301K (82F), resulting in poor module performance and current density limitations due to a low water feed driving force.

Low product gas dew points, however, can also be obtained by gas expansion or by a combination of gas expansion and the use of a Dehumidifier Module (DM). The latter removes water vapor electrolytically from the product gases forming additional O_2 and H_2 in the respective gas passages. A detailed description of the DM development activities performed under this program is presented later.

Reducing the total gas pressure by a fixed ratio results in an equal ratio reduction in the partial water vapor pressure of the product gases. Figure 2 shows product gas dew points as a function of total operating pressure for various operating temperatures, electrolyte concentrations and cabin atmosphere

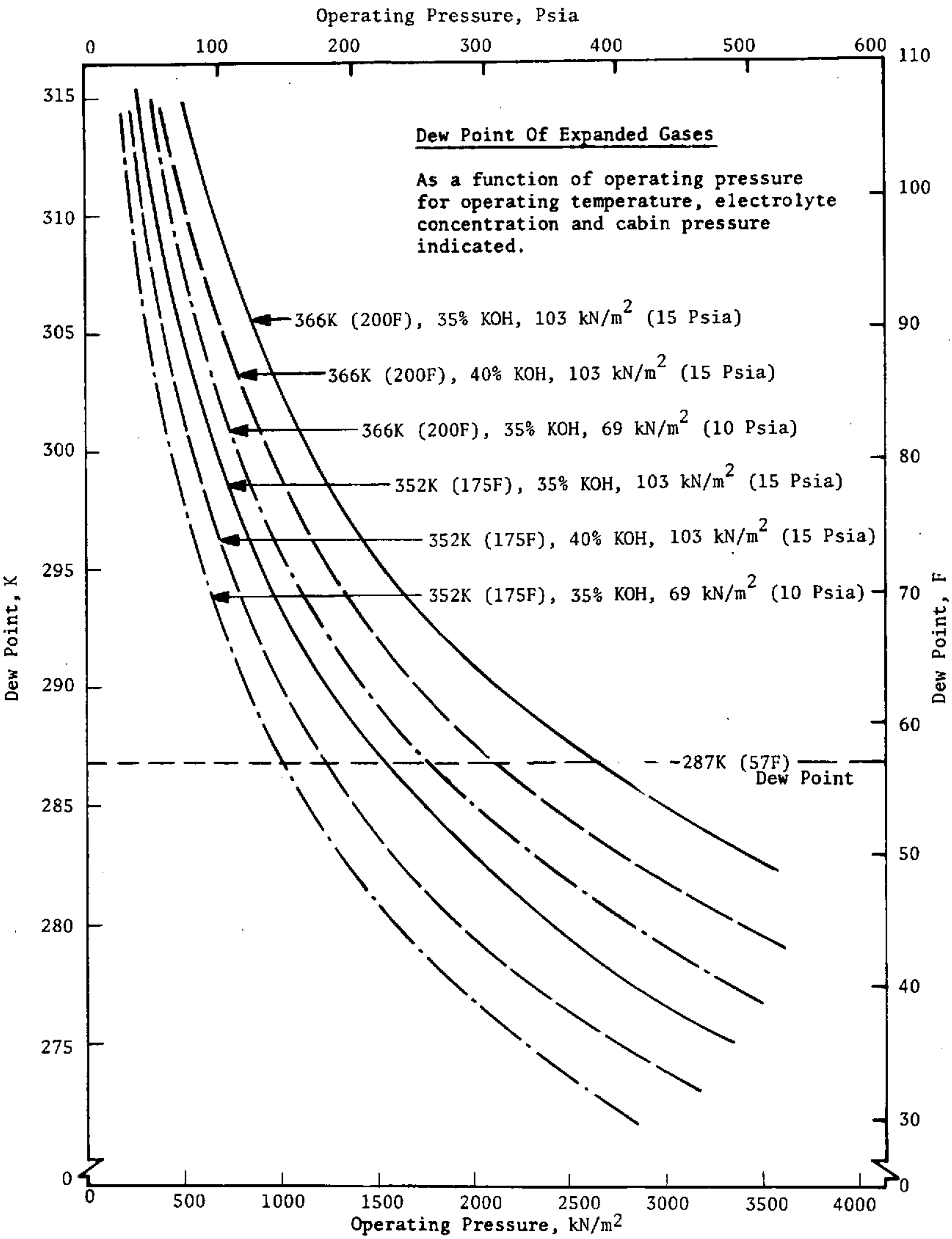


FIGURE 2 PRODUCT GAS DEW POINT

pressure levels. Figure 2 indicates that low operating temperatures, low electrolyte concentration, low cabin atmospheric pressures, and high system operating pressures result in a low dew point level.

The DM accepts the SFWEM product gases (O_2 and H_2) to electrolytically remove a portion of the water vapor contained in them. The gases are then reduced in pressure by expansion through regulators, which reduces the dew points below the desired level, i.e., 287K (57F). An optimization with respect to SFWEM and DM operating pressures, temperatures, and electrolyte concentrations had to be performed to arrive at the overall system optimum operating conditions.

Elimination of Degassing Requirements

Accumulation of gases within the SFWES and feed cavities of individual cells of a SFWEM causes performance degradation and eventual system failure. A design goal of the SFWEM was to allow for operation without the requirement for feed water or feed water cavity degassing. Previous operation with single static feed water electrolysis cells had demonstrated operation for 300 hours at 108 mA/cm^2 (100 ASF) and 100 hours at 323 mA/cm^2 (300 ASF) without degassing requirements. An objective of this program was to totally eliminate the need for degassing.

The general design approach for the advanced SFWEM was to eliminate possible sources and causes of gas accumulations within the water feed cavities rather than to treat the problem after gases had accumulated.

Three basic sources for gassing were identified:

1. Cross-leakage of H_2 into the water feed cavities.
2. Stray electrolysis within liquid passages and cavities.
3. Release of dissolved gases from the makeup feed water.

Hydrogen Cross-leakage

Cross-leakage of H_2 into the water feed cavities results from structural cell/ matrix failure due to excessive pressure differentials or water feed matrix dryout. This dryout was normally caused by gas accumulation due to the other two causes of gas liberation or by excessive heat release at the cell electrodes.

The SFWEM was designed with proper structural matrix support proven in past water electrolysis module designs, while the test system was designed with monitoring instrumentation that prevents out-of-tolerance pressure differentials from existing.

Stray Electrolysis

One of the most detrimental sources of gassing was stray (intercell) electrolysis. Since gas evolution by electrolysis requires a metallic surface, the elimination or minimization of any metallic parts within the liquid loop or within the feed cavities was essential.

The rate of stray electrolysis was a function of the voltage differential between two metallic surfaces contacted by a common electrolyte media. The distance between these metallic parts and the electrolyte media resistivity also affected the amount of gases liberated for a given voltage difference. The greater the distance for a given voltage, the smaller the chance of gas liberation. To minimize the electrical driving potentials the module must not be electrically grounded but must be allowed to "float." The absence of a metallic recirculation loop and the presence of only water in the water feed supply line (unmixed with KOH due to density gradients) also minimizes stray electrolysis. The SFWEM was designed accordingly.

Dissolved Gases

The water fed to the SFWEM tends to be saturated with air or N_2 at its supply or storage pressure and temperature. These dissolved gases are potential sources for gas accumulation in the water feed compartment. To eliminate this source of gassing required investigation of the parameters that affect gas solubility.

Solubility of gases in water is a function of absolute pressure, temperature, and type of gas involved. Solubility of gases in aqueous solutions of electrolytes is governed by these same parameters, but in addition is also affected by the presence of the electrolyte. In general, solubility of gases decreases with increase in temperature, electrolyte concentration, and absolute pressure level.

For the typical SFWEM operating conditions, the solubility of air in the feed compartment liquid is only 1/15 that of the incoming feed water. This decrease results due to a factor of ten reduction caused by the 35% KOH concentration and a factor of 1.5 reduction caused by the temperature increase from 297 to 352K (75 to 175F).

Since an aqueous solution of electrolyte is used in the feed cavities of a SFWEM and since elevated temperatures are desired for optimum performance, operating pressure remains the only small parameter that can be adjusted to preclude gas dissolution within the feed compartments.

For the SFWEM design the total operating pressure must be raised by a ratio equivalent to the ratio in loss of solubility due to the combined effects of temperature and the electrolyte concentration. Since solubility is decreased by a factor of 15, operating pressure must be increased by the same factor above the feed water source pressure. This means a minimum projected operating pressure for the SFWEM of 1551 kN/m^2 (225 psia).

Module Sizing

The size of an electrolysis module is basically determined by O_2 generation requirements. Once this number has been established trades between number of cells, current flowing, current density and active electrode area and dimension can be performed.[3] Practical limitations as to current levels and cell size dimensions will normally govern final module sizing. High current density and large active areas, for example, may result in excessive current levels causing high IR losses and increased equivalent system weights.

The SFWEM was designed for a range in O_2 generation rate of 0.680 to 0.907 kg/d (1.5 to 2 lb/day) while maintaining the active area of each individual cell between 92.9 and 185.8 cm^2 (0.1 and 0.2 ft^2). It was designed to have six cells, each having an active area of 92.9 cm^2 (0.1 ft^2). The resulting current level is 21.2 amps for an O_2 generation rate of 0.907 kg/d (2 lb/day) at a current density of 227 mA/cm^2 (211 ASF). The dimensions of the active area are 11.38 x 8.20 cm (4.48 x 3.23 in). This resulted in an area of 92.9 cm^2 (0.1 ft^2) when including the effects of corner radii.

Nominal Design Point

The nominal design point for the SFWEM was selected to be an O_2 generation rate of 0.907 kg/d (2.0 lb/day) while operating at 1724 kN/m^2 (250 psia) and 352K (175F) with an electrolyte concentration of 35% KOH (by weight). Based on analytical considerations, the need for condenser/separators and for feed water cavity degassing would be eliminated at these conditions. Detailed mass and heat balances for the SFWEM itself and for the total test system at the nominal design point were performed and are presented in Figures 3 and 4, respectively.

Fluid Flow Calculations

For operation at other than nominal design point, the flow of the four process fluids (O_2, H_2, water, and coolant) interfacing with the SFWEM can be readily calculated based on Faraday's Law and standard humidification and heat balance equations.

Oxygen Flow

The flow rate of O_2 can be calculated as a function of current flow by the equation:

$$\dot{m}_{O_2} = 2.98 \times 10^{-4} IN \tag{4}$$

where

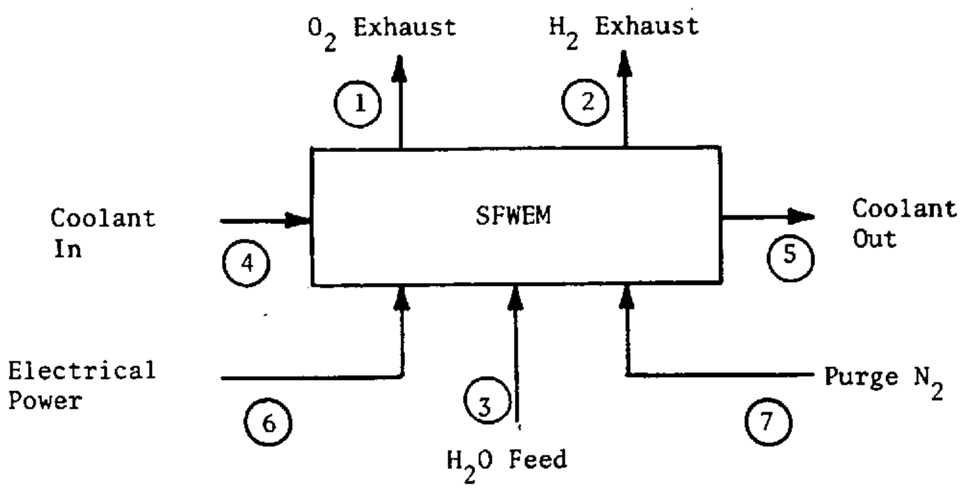
$\dot{m}_{O_2}$ = flow rate of O_2 generated, kg/h

I = current flow through cells electrically connected in series, A

N = number of series-connected cells

Hydrogen Flow

The flow rate of H_2 can be calculated as a function of current flow by the



1. O_2 Exhaust

O_2 Flow	0.907 kg/d (2.000 Lb/Day) 476 cc/Min
Water Flow (Vapor)	0.0073 kg/d (0.016 Lb/Day)
Total Pressure	1724 kN/m^2 (250 Psia)
Water Vapor Pressure	24 kN/m^2 (180 mm Hg)
Temperature	352K (175F)

2. H_2 Exhaust

H_2 Flow	0.114 kg/d (0.252 Lb/Day) 952 cc/Min
Water Flow (Vapor)	0.0145 kg/d (0.032 Lb/Day)
Total Pressure	1689 kN/m^2 (245 Psia)
Water Vapor Pressure	24 kN/m^2 (180 mm Hg)
Temperature	352K (175F)

3. Water Feed

Water Flow	1.043 kg/d (2.300 Lb/Day) 0.725 cc/Min (Liquid)
Pressure	1655 kN/m^2 (240 Psia)
Temperature	294K (70F)

4. Coolant In

Type	Water
Flow	27.2 kg/h (59.9 Lb/Hr)
Pressure	154 kN/m^2 (22.4 Psia)
Temperature	350K (171F)

5. Coolant Out

Type	Water
Flow	27.2 kg/h (59.9 Lb/Hr)
Pressure	105 kN/m^2 (15.2 Psia)
Temperature	352K (174F)

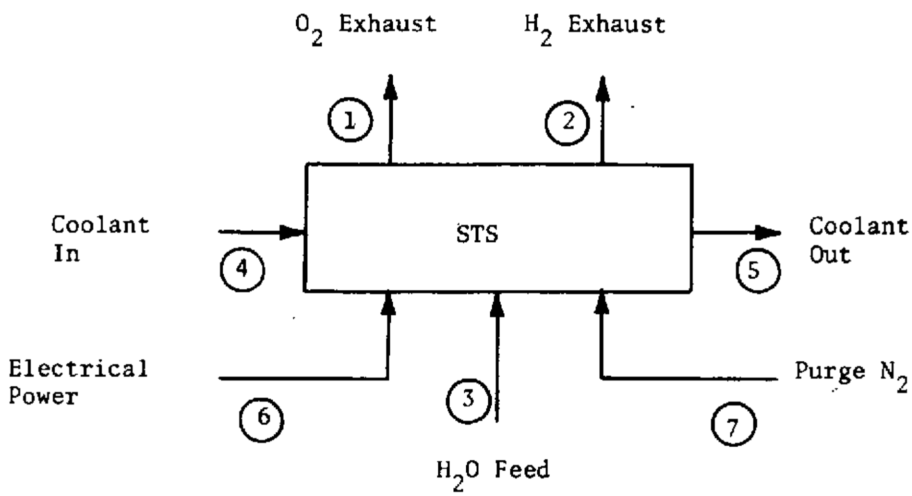
6. Electrical Power

Type	DC
Current	21.1 A
Cell Voltage	1.92 VDC
Module Voltage	11.52 VDC
Power	243 W

7. Purge N_2

Flow	As Req.
Pressure	138 kN/m^2 (20 Psia)
Temperature	294K (70F)

FIGURE 3 SFWEM MASS AND HEAT BALANCE



1. <u>O_2 Exhaust</u>

O_2 Flow	0.907 kg/d (2.000 Lb/Day) 476 cc/Min
Water Flow (Vapor)	0.0073 kg/d (0.016 Lb/Day)
Total Pressure	103 kN/m^2 (15 Psia)
Water Vapor Pressure	1.44 kN/m^2 (10.8 mm Hg)
Temperature	294K (70F)
Dew Point	285.5K (54.5F)

2. <u>H_2 Exhaust</u>

H_2 Flow	0.114 kg/d (0.252 Lb/Day) 952 cc/Min
Water Flow (Vapor)	0.0145 kg/d (0.032 Lb/Day)
Total Pressure	103 kN/m^2 (15 Psia)
Water Vapor Pressure	1.47 kN/m^2 (11.0 mm Hg)
Temperature	294K (70F)
Dew Point	285.8K (55F)

3. <u>Water Feed</u>

Water Flow	1.043 kg/d (2.300 Lb/Day) 0.725 cc/Min (Liquid)
Pressure	310 kN/m^2 (45 Psia)
Temperature	294K (70F)

4. <u>Coolant In</u>

Type	Water
Flow	29.1 kg/h (64.2 Lb/Hr)
Pressure	310 kN/m^2 (45 Psia)
Temperature	277-289K (40-60F)

5. <u>Coolant Out</u>

Type	Water
Flow	29.1 kg/h (64.2 Lb/Hr)
Pressure	241 kN/m^2 (35 Psia)
Temperature	Inlet + 5.6K (10F)

6. <u>Electrical Power</u>

Type	115 VAC, 400 Hz, 24-32 VDC
Power	
DC	286 W
AC	100 W

7. <u>Purge N_2</u>

Flow	As Req.
Pressure	310 kN/m^2 (45 Psia)
Temperature	294K (70F)

FIGURE 4 SFWEM TEST SYSTEM MASS AND HEAT BALANCE

equation:

$$\dot{m}_{H_2} = 3.76 \times 10^{-5} IN \tag{5}$$

where

$\dot{m}_{H_2}$ = flow rate of H_2 generated, kg/h

Water Flow for Electrolysis

The flow rate of water decomposed electrochemically can be calculated as a function of current by the equation:

$$\dot{m}_{H_2O} = 3.36 \times 10^{-4} IN \tag{6}$$

where

$\dot{m}_{H_2O}$ = flow rate of water consumed, kg/h

Water Flow for Humidification

The quantity of water carried from the cell via the humidified gas products can be calculated by the equation:

$$\dot{m}_{H_2O}(\text{humid}) = \dot{m}_{H_2} W_{H_2} + \dot{m}_{O_2} W_{O_2} \tag{7}$$

where

$\dot{m}_{H_2O}$(humid) = H_2O loss rate via humid gases, kg/h (lb/hr)

$\dot{m}_{H_2}$ = flow rate of H_2, kg/h (lb/hr)

$\dot{m}_{O_2}$ = flow rate of O_2, kg/h (lb/hr)

W_{H_2} = specific humidity ratio, kg H_2O/kg dry H_2 (lb H_2O/lb dry H_2)

W_{O_2} = specific humidity ratio, kg H_2O/kg dry O_2 (lb H_2O/lb dry O_2)

The specific humidity ratio of the gases is:

$$W_g = \frac{M_w}{M_g} \frac{P_v(g)}{P_t(g) - P_v(g)} \tag{8}$$

where

W_g = specific humidity ratio of gas (O_2 or H_2)

M_w = molecular weight of water

M_g = molecular weight of gas (O_2 or H_2)

$P_v(g)$ = partial pressure of water vapor in gas over electrolyte at cell temperature and concentration existing in gas compartment in consistent pressure units.

$P_t(g)$ = total pressure of gas and water vapor in gas compartment in consistent pressure units.

Coolant Flow

The required coolant water flow rate can be calculated from the amount of heat to be removed from the SFWEM and the desired temperature rise in the coolant flow (approximately equivalent to desired module temperature gradient). Figure 5 shows this relationship graphically for water as the coolant. The amount of heat generated within the module and needed to use Figure 5 must first be determined from Figure 6. Conductive or evaporative heat losses, if significant, must be subtracted from the cooling load before entering Figure 5.

Module Design

In the design of the SFWEM major emphasis was placed on avoiding the problems and limitations identified in the survey of water electrolysis modules and systems. The resulting cell configuration is shown, in a cross-section form, in Figure 7. Table 2 identifies the numbered items shown on the figure, including materials of construction of the individual cell components.

Cell Configuration

As shown in Figure 7, each of the cells has four cavities: (1) the O_2 cavity, (2) the H_2 cavity, (3) the water feed cavity, and (4) the liquid coolant cavity. Intercavity sealing is achieved by squeezing the cell and water feed matrices between the polysulfone frame components forming the O_2 and H_2 and O_2 and water feed cavities, respectively. The cell frame and anode current collector provide passages for the liquid coolant. The cell cavities are internally manifolded. The cavities of each type of fluid are connected in parallel while the cells are connected electrically in series. The manifolding arrangement for the cells are also shown in Figure 7.

The major features included in the cell design are:

1. Isolation of all feed water inlet and feed water cavity fluid circulation ports from metallic components.

2. Calculated sizing of water feed cavity manifolds and ports to prevent air bubble blockage.

3. Low H_2 cavity thickness to decrease diffusional resistance to water vapor.

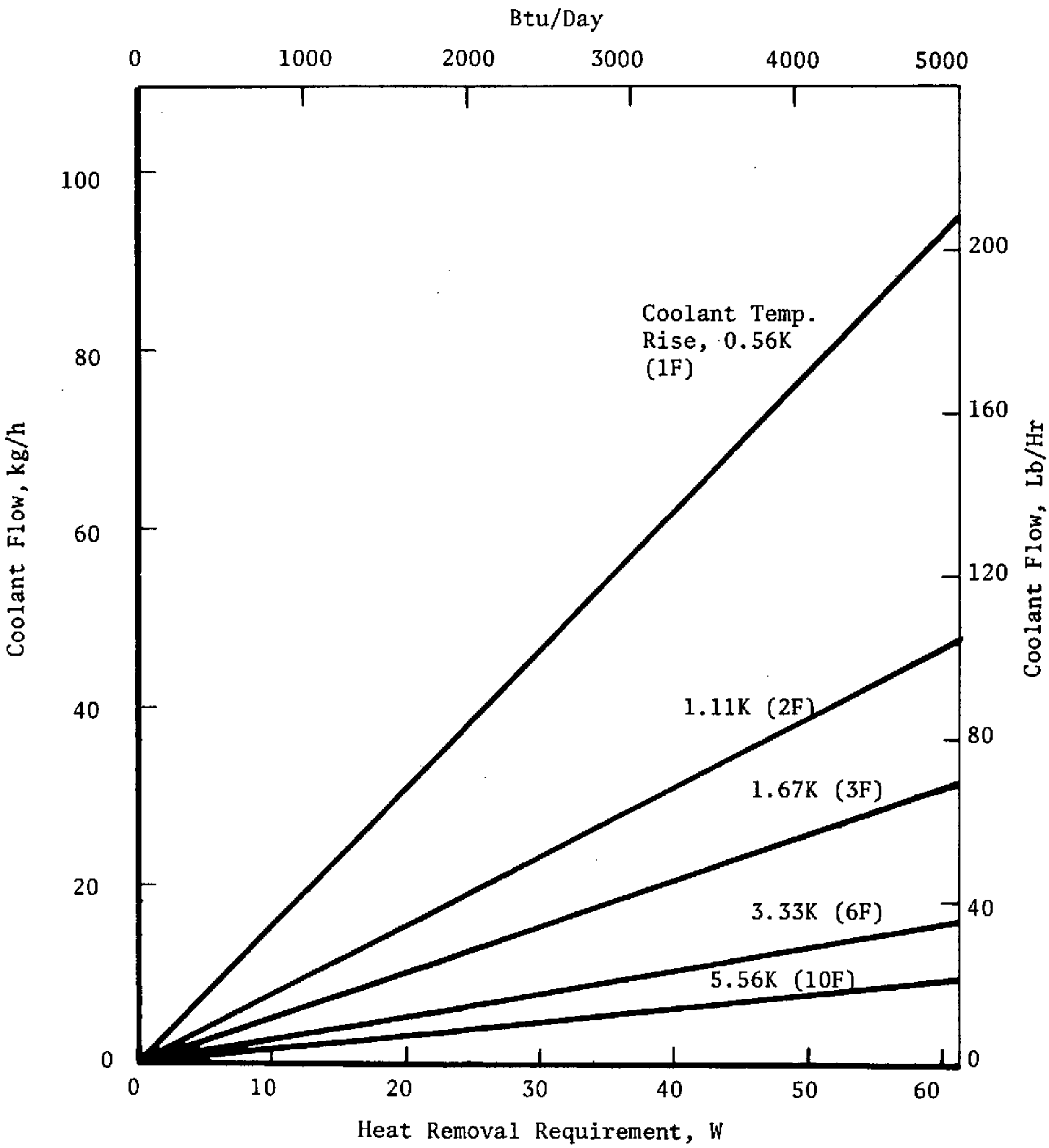


FIGURE 5 PURE WATER COOLING CAPACITY

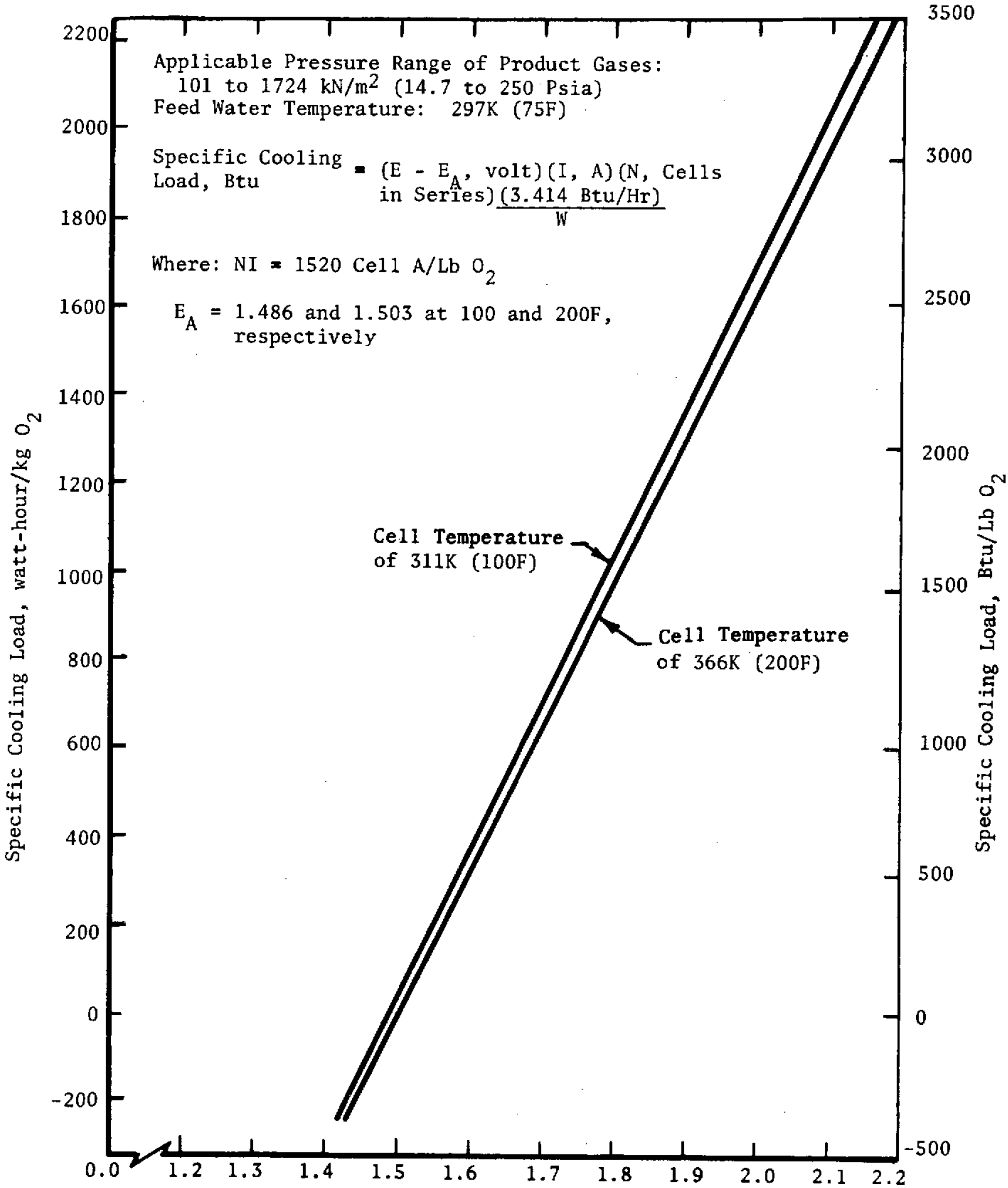
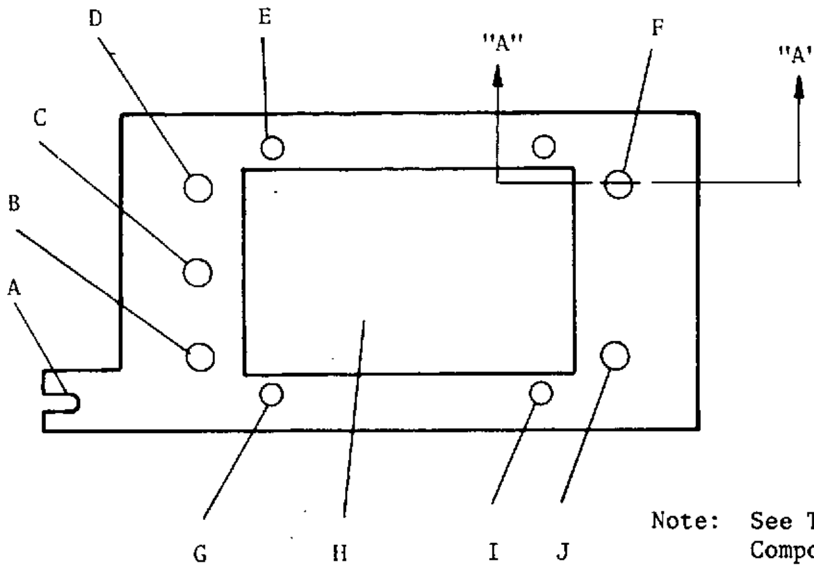


FIGURE 6 ELECTROLYSIS WASTE HEAT GENERATED VERSUS CELL VOLTAGE



Note: See Table 2 for Component, Process Fluid, and Current Tab Identification

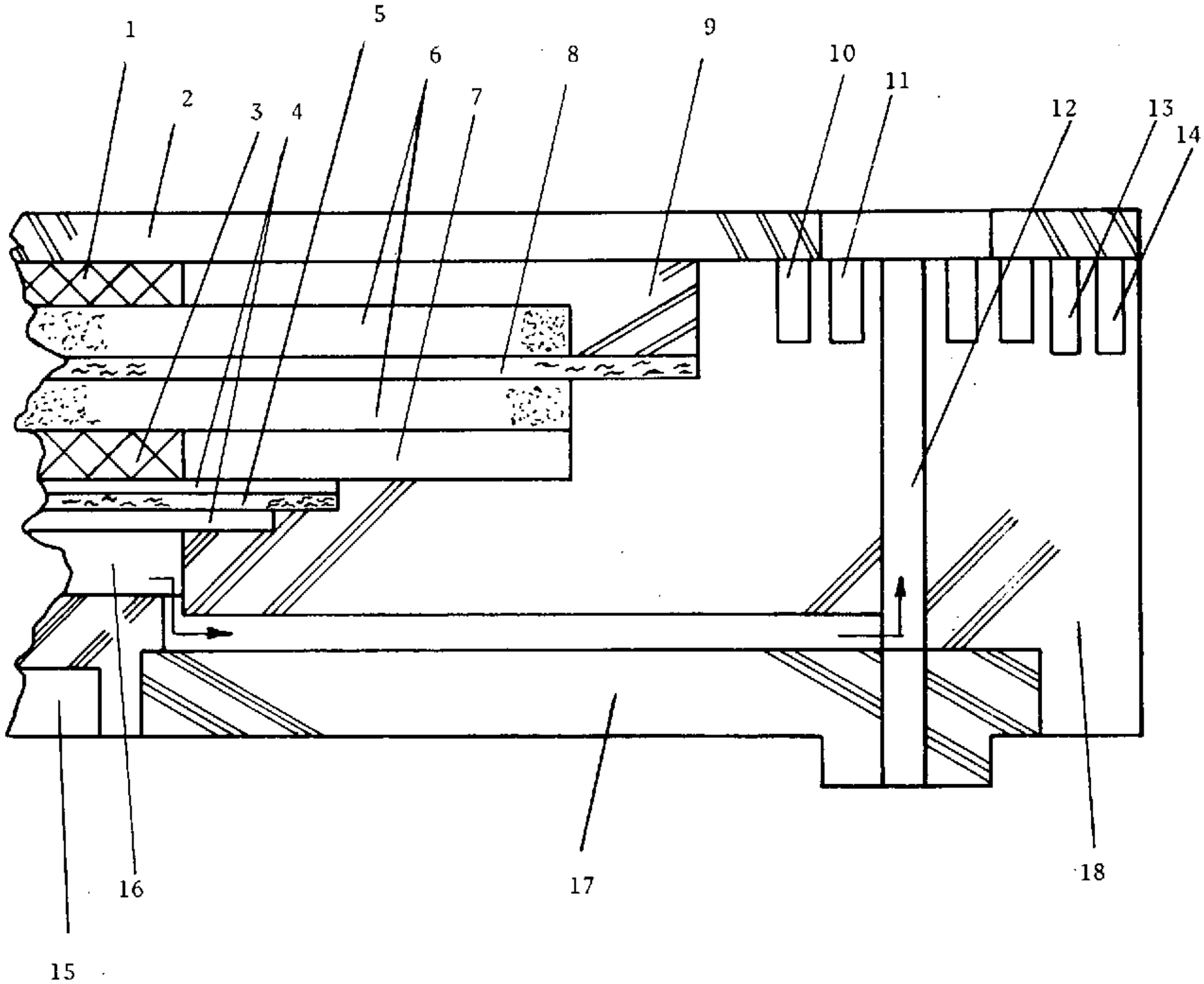


FIGURE 7 SFWEM CELL CROSS SECTION

TABLE 2 SFWEM CELL COMPONENTS

1 Oxygen Cavity with Exmet Spacer, Gold-Plated Nickel, 0.051 cm (0.020 In)[(a)]
2 Anode Current Collector, Gold-Plated Nickel, 0.051 cm (0.020 In)
3 Hydrogen Cavity with Exmet Spacer, Gold-Plated Nickel, 0.051 cm (0.020 In)
4 Feed Matrix Support Screen, Teflon, 0.025 cm (0.010 In)
5 Water Feed Matrix, Custom-Blended Asbestos, 0.030 cm (0.012 In, compressed)
6 Activated Electrodes, Porous Nickel, 0.076 cm (0.030 In)
7 Cathode Current Collector Frame, Gold-Plated Nickel, 0.051 cm (0.020 In)
8 Cell Matrix, Custom-Blended Asbestos, 0.025 cm (0.010 In, compressed)
9 Compression Frame, Polysulfone, 0.127 cm (0.050 In)
10 Outer Manifold O-Ring, Ethylene Propylene
11 Inner Manifold O-Ring, Ethylene Propylene
12 Manifold for Feed Compartment Fluid
13 Inner Double O-Ring, Ethylene Propylene
14 Outer Double O-Ring, Ethylene Propylene
15 Coolant Cavity, 0.114 cm (0.045 In)
16 Water Feed Cavity, 0.114 cm (0.045 In)
17 Manifold Cover, Polysulfone
18 Cell Frame, Polysulfone, 0.787 cm (0.310 In)

A Current and Voltage Tap
B Water Feed Compartment Outlet
C Feed Water In
D Hydrogen Outlet
E Coolant Outlet
F Nitrogen Purge Inlet (O_2 Side)
G Oxygen Outlet
H Active Area, 8.20 cm x 11.38 cm (3.23 In x 4.48 In)
I Coolant Inlet
J Nitrogen Purge Inlet (H_2 Side)
K Water Feed Compartment Inlet

(a) Component or cavity thickness dimensions

4. Electrode-to-matrix thickness ratio of approximately 6:1 to increase moisture tolerance.

5. Use of custom-blended cell matrices to provide increased stability to pressure differentials.

6. Use of porous nickel (Ni) plaque electrodes activated for high cell performance, i.e., low cell voltages at a given current density.

7. Liquid cooling to provide uniform temperature distribution.

8. Low volume construction by providing three cells per inch.

9. Internal electrical connections between adjacent cells for low intracell IR losses.

10. Double O-ring seals between internal fluid cavities and the environment for increased reliability.

11. Gold-plated Ni current collectors and gas cavity spacers for long-term stability to the electrolyte environment.

12. Only one single cell housing frame required per cell, injection molded from polysulfone for ease in fabrication.

13. Water feed manifold located on top of the cell with individual feed tubes protruding to the bottom of each feed cavity to prevent electrolyte maldistribution due to density gradients.

Module Configuration

The SFWEM consists of six cells retained between two stainless steel endplates. The two end cells were thermally insulated from the stainless steel endplates by two 0.64 cm (1/4 in) thick polysulfone insulation plates to minimize thermal end effects. Compression force was applied by ten 1.43 cm (9/16 in) diameter stainless steel bolts.

The completed SFWEM weighed 35.8 kg (78.9 lb) with the majority of the weight (32.5 kg (71.8 lb)) concentrated in the endplates and bolts. Flight versions of the endplates would be constructed with honeycomb material which would reduce their weight by 60 to 70%. The SFWEM had a volume of 0.00909 m^3 (0.321 ft^3) and a size of 11.73 cm (4.62 in) by 25.4 cm (10 in) by 30.5 cm (12 in).

Internal Current Connection

The SFWEM used internal current connections between the anode current collector of one cell and the cathode current collector of the adjacent cell. This approach decreased internal resistance and simplified cell design. Figure 8 shows the method used to interconnect the two current collectors. A flat-head

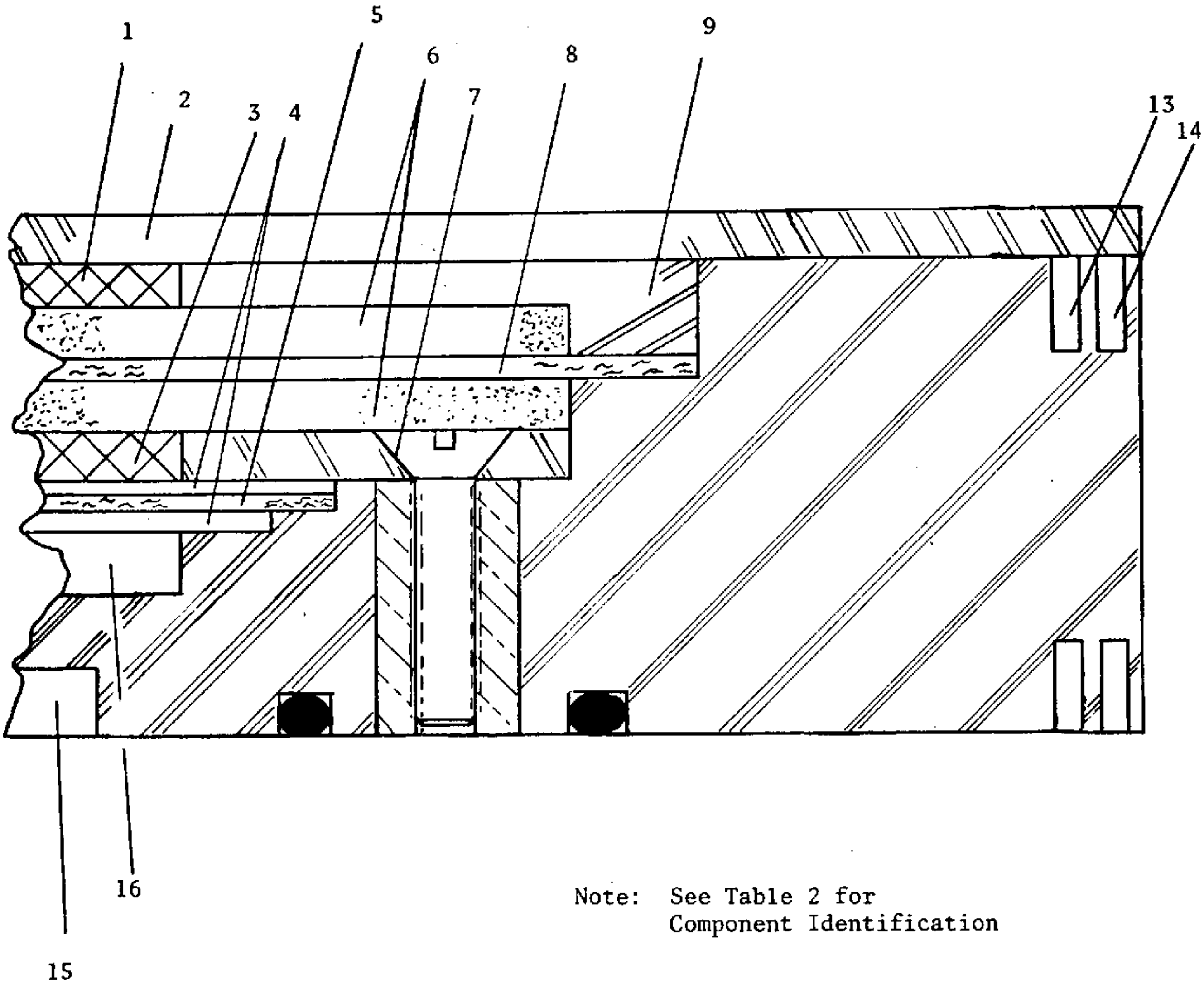


FIGURE 8 INTERNAL INTERCELL CURRENT CONNECTION

screw fastens the cathode current collector frame onto a post, which was resistance-welded to the anode current collector of the adjacent cell, to provide the electrical conduction path. Sealing between the liquid coolant compartment and the H_2 compartment required around the current post was achieved by a single O-ring. Four such locations for current conduction were provided per cell, one at each of the four corners of the cathode current collector frame.

Fluid Manifolding

Particular attention was paid to manifolding of the five different fluids that flow into, through, or out of the SFWEM. These fluids were: (1) feed water, (2) liquid coolant, (3) N_2 for purge, (4) generated O_2, and (5) generated H_2.

To prevent loss of current efficiency through intercell electrolysis accompanied by an accumulation of gases in the water feed manifolds and cavities, the electrolyte in the feed water cavity and the water feed system were isolated from all metallic components within the module. This isolation was achieved by using polysulfone manifold covers with raised surfaces extending through the metallic current collectors, thus providing polysulfone-to-polysulfone contact and isolating the electrolyte from the Ni current collectors. Passage of the electrolyte and water feed through the stainless steel endplates constituted an additional area where intercell electrolysis or gas generation could occur. This problem was solved by designing access ports to the liquid compartments lined with polysulfone sleeves and sealed with a modified O-ring seal fitting. A section of the typical liquid pass-through through an endplate is shown in Figure 9.

Figures 10 through 13 show sections through the manifolding regions representative of coolant inlet or outlet, water feed and electrolyte inlet or outlet, N_2 inlet or O_2 outlet, and N_2 inlet or H_2 outlet, respectively. Manifold covers were only required for access to the internal cell compartments, i.e., H_2 and water feed compartments. The embossed surface that passed through the anode current collectors on the manifold cover for the H_2 port was included, although not required, for isolation from the metallic surfaces, to enable use of commonality manifold covers.

All fluid manifolds and ports were located in a geometrical arrangement to enhance fluid passage through the rectangular active cell area, i.e., inlet passages were located diagonally opposite the outlet passages.

Module Fabrication

Each of the SFWEM's six cells consisted of eight polysulfone parts; cell frame, compression frame, internal water feed cover, and five fluid manifold covers. As part of the program, an evaluation was performed to compare standard machining techniques with injection molding for the plastic parts. The results of the study[11] showed that it was more cost-effective to use the injection molding technique for the plastic cell parts when considered over the complete development time frame. Each cell also had two gold-plated Ni current collectors, the anode and the cathode frame. These parts were fabricated using standard machining

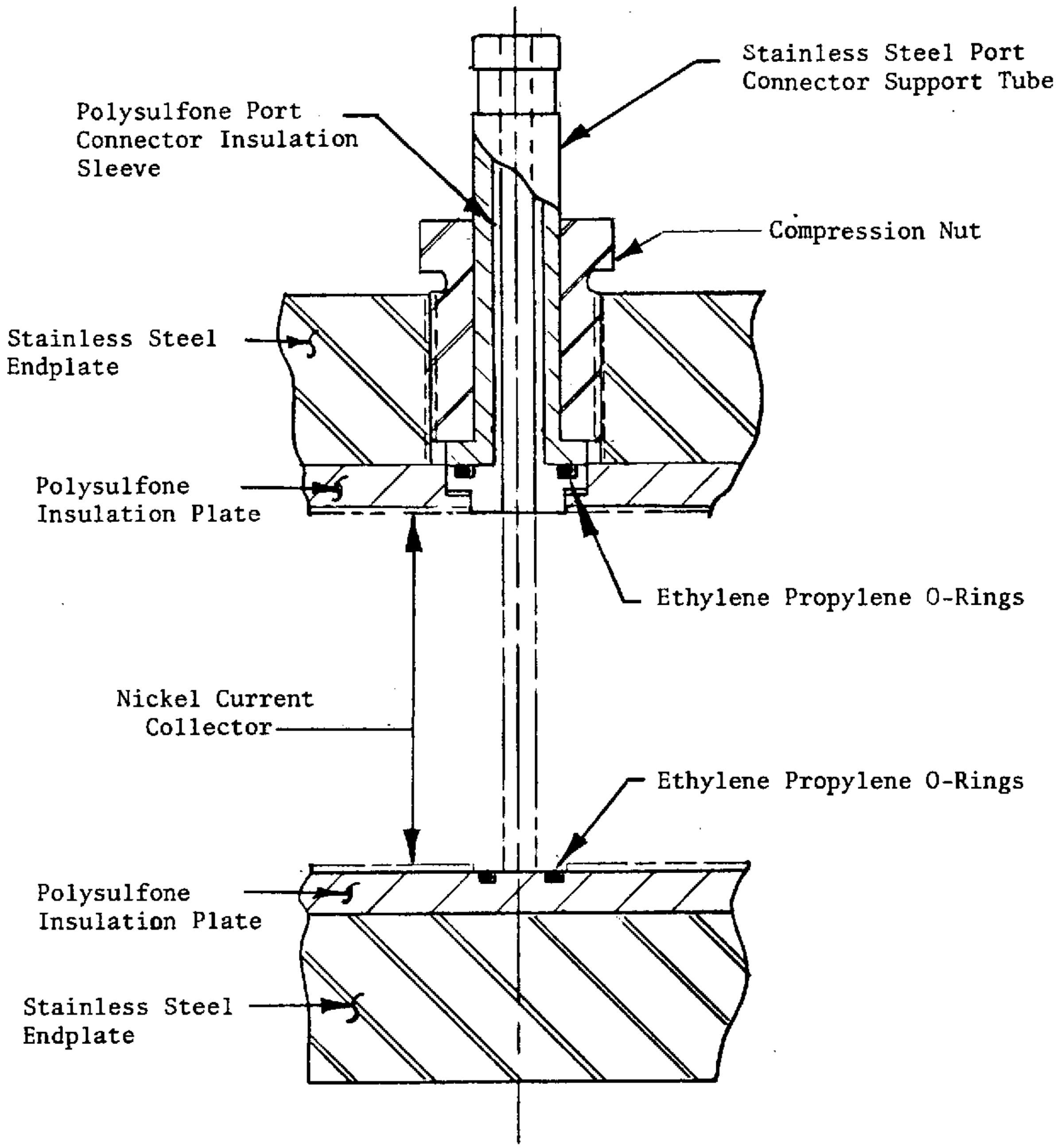


FIGURE 9 LIQUID MANIFOLD ISOLATION FROM ENDPLATE

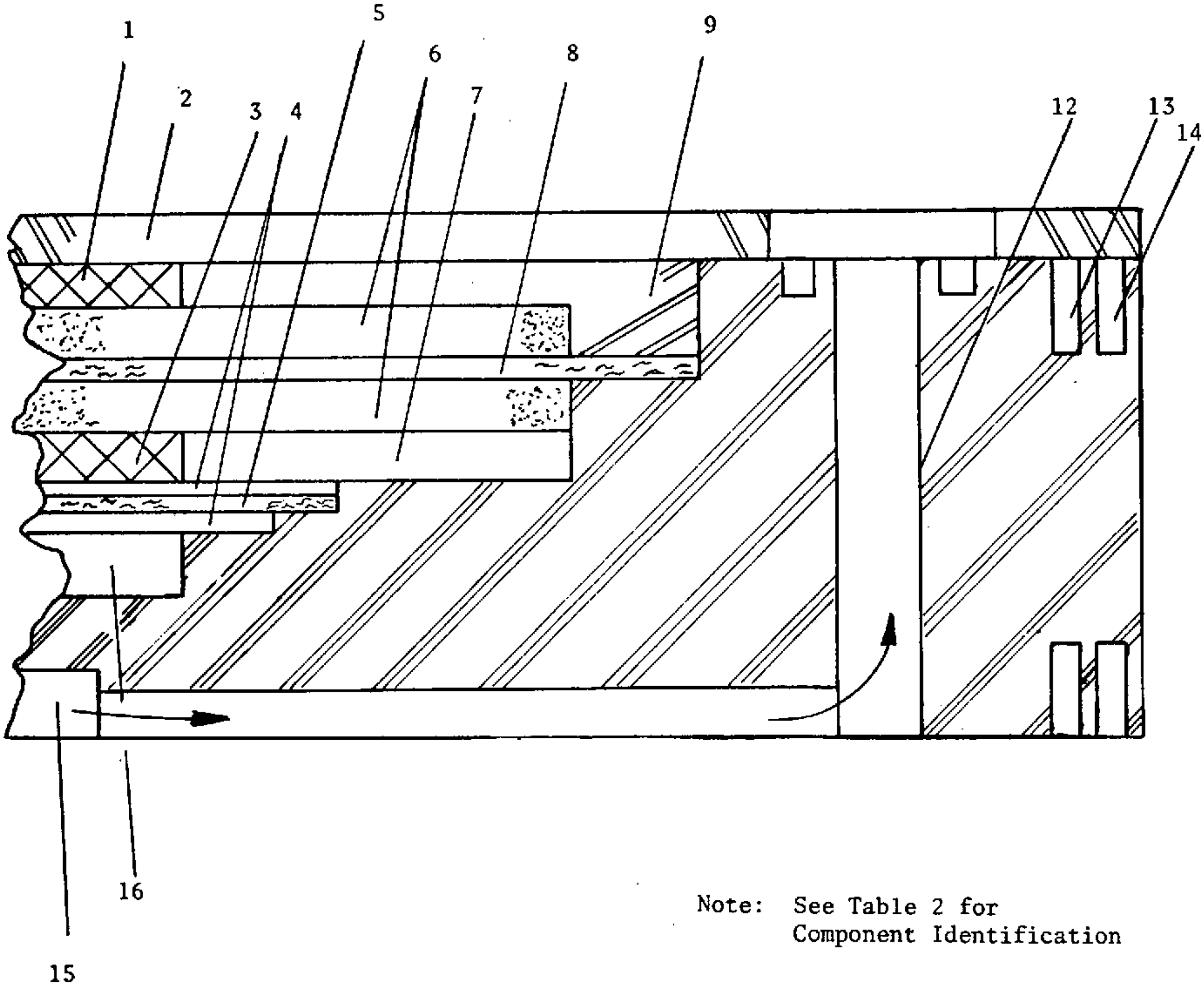
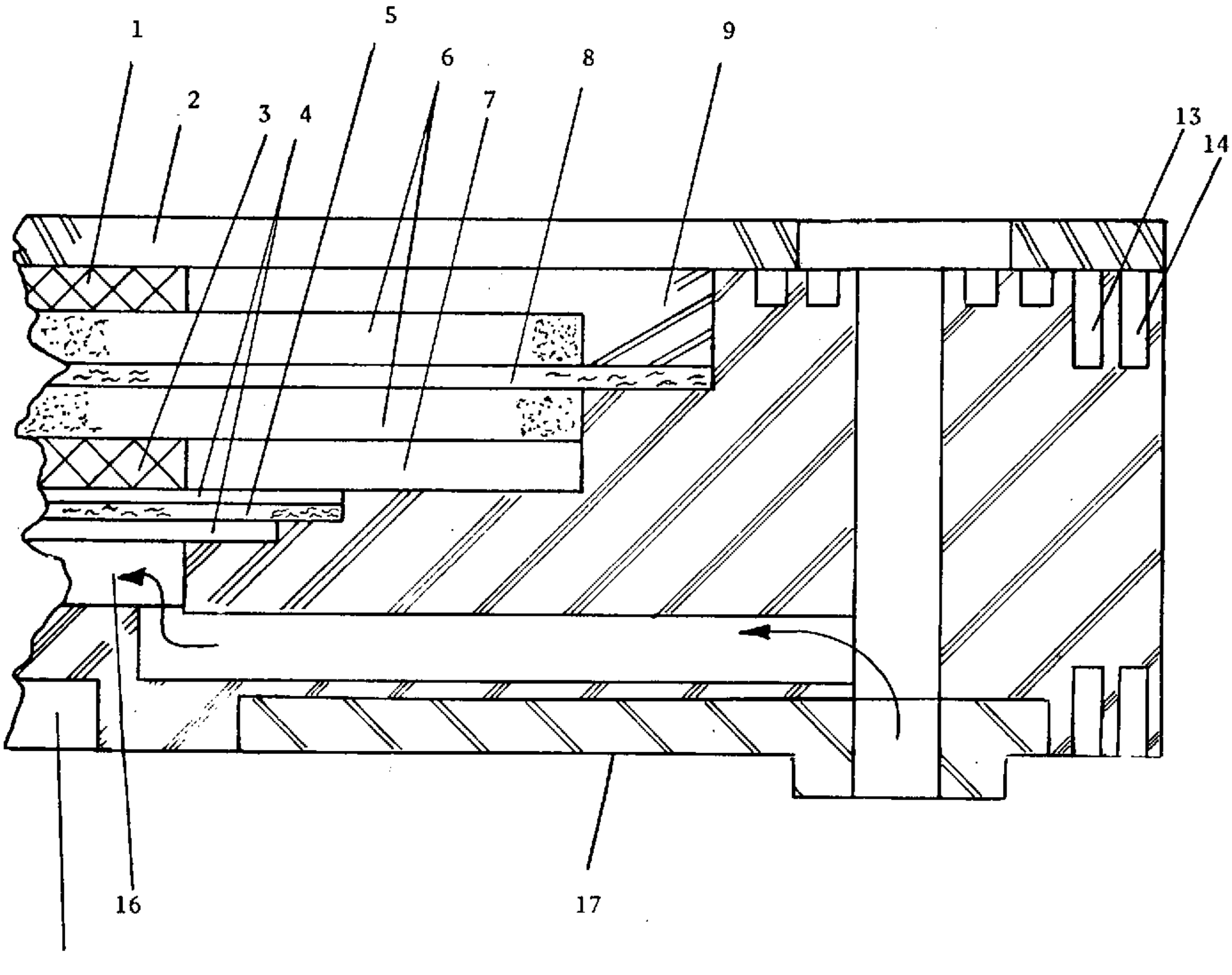
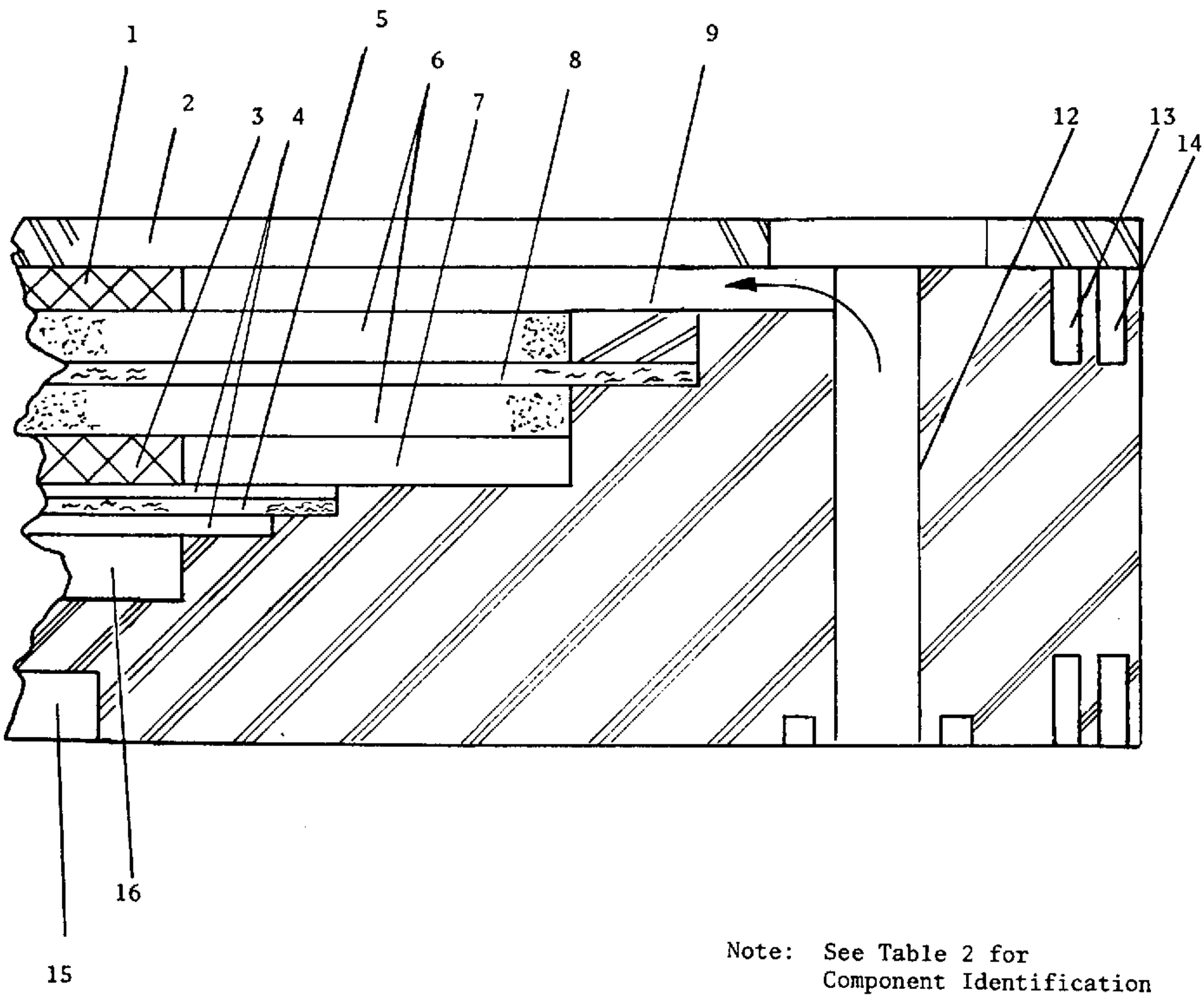


FIGURE 10 LIQUID COOLANT MANIFOLD CROSS SECTION



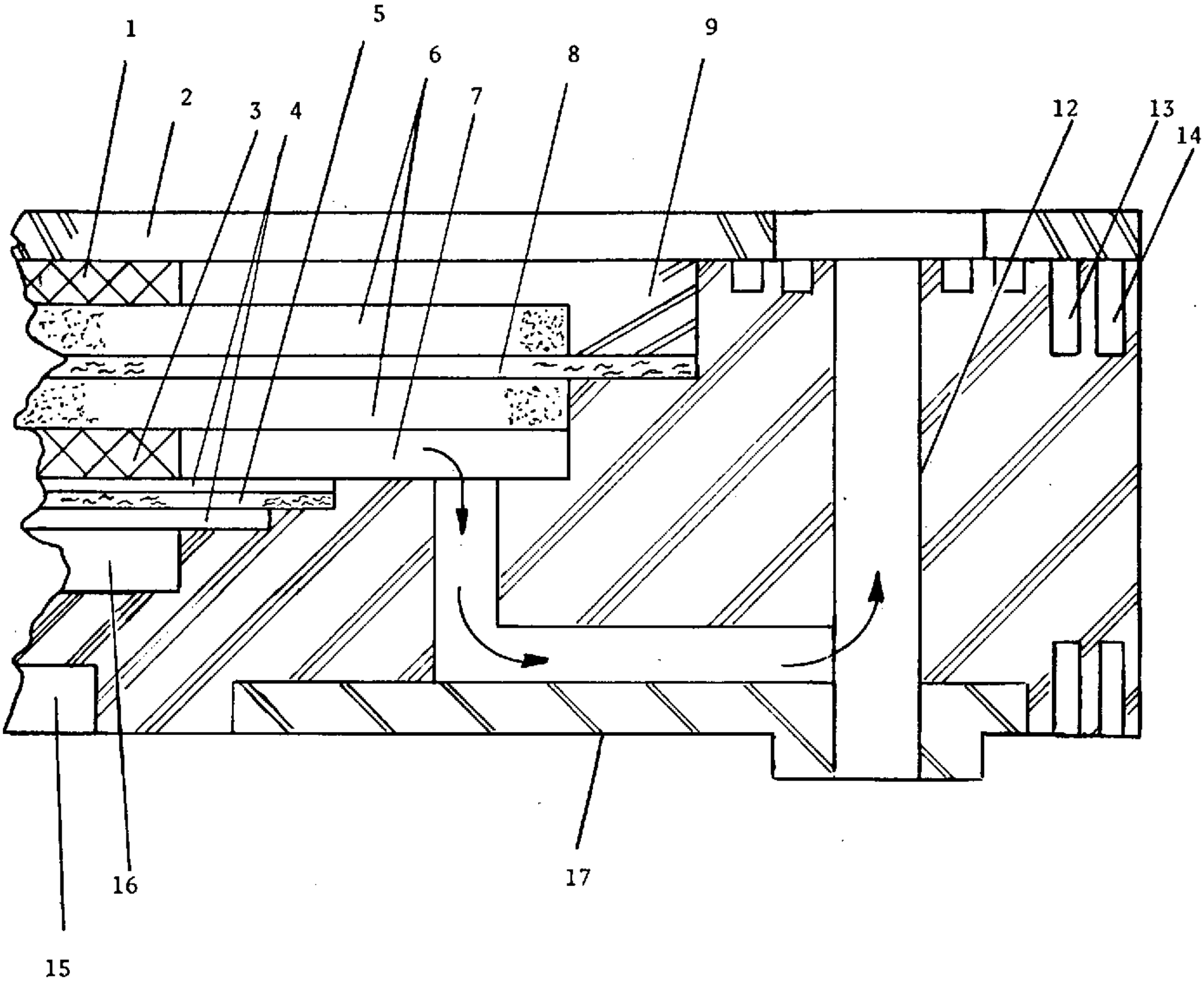
Note: See Table 2 for
Component Identification

FIGURE 11 WATER FEED COMPARTMENT MANIFOLD
CROSS SECTION



Note: See Table 2 for Component Identification

FIGURE 12 OXYGEN COMPARTMENT MANIFOLD CROSS SECTION



Note: See Table 2 for Component Identification

FIGURE 13 HYDROGEN COMPARTMENT MANIFOLD, CROSS SECTION techniques. The remaining parts for the cells were the electrode-electrolyte retaining matrix-electrode sandwich and a Teflon screen-asbestos feed matrix-Teflon screen water feed membrane which separated the water feed cavity from the H_2 cavity. Expanded metal screen (gold-plated Ni) formed the O_2 and H_2 gas cavities.

The electrodes were activated on sintered porous Ni plaques. The water feed and cell matrices were custom-blended asbestos.

All sealing was accomplished with ethylene propylene O-rings with double O-rings used for all seals which saw total module pressure. Figure 14 is a photograph of the parts of one cell.

The six cells of the SFWEM were sandwiched between two thermal insulating machined polysulfone endplates. These were held between two machined stainless steel endplates which gave structural strength to the module. The SFWEM was held together and the compression necessary to seal the cells was provided by ten stainless steel bolts.

SFWEM GROUND SUPPORT ACCESSORIES

The GSA for the SFWEM consist of the SFWEM Test System (STS), the condenser separators, the Gas Separator Unit (GSU), and sources for the feed water cooling water, electrical power, and purge N_2.

SFWEM Test System

The STS provided the necessary controls and fluid supplies to allow testing of the SFWEM over its designed operating range. Automatic controls were included to provide safe and easy operation. In addition, manual controls allowed flexibility in operation needed during parametric and off-design testing. Automatic monitoring provided protection for both equipment and personnel.

STS Specifications

The STS was designed according to the specifications outlined in Table 3. The STS was also designed to allow operation of the SFWEM with and without condenser/separators, operation with and without the DM, and operation with continuous or intermittent circulation of the feed water cavity fluid.

STS Operation

The STS provided the SFWEM with product gas pressure control, temperature control, water feed addition, and N_2 purging. The STS also allowed for optional operating modes utilizing condenser/separators, the DM, and circulation of the fluid contained in the water feed compartments. Electrical control and monitoring instrumentation was also provided by the STS. Figure 15 is a schematic of the STS and Figure 16 is a photograph of it.

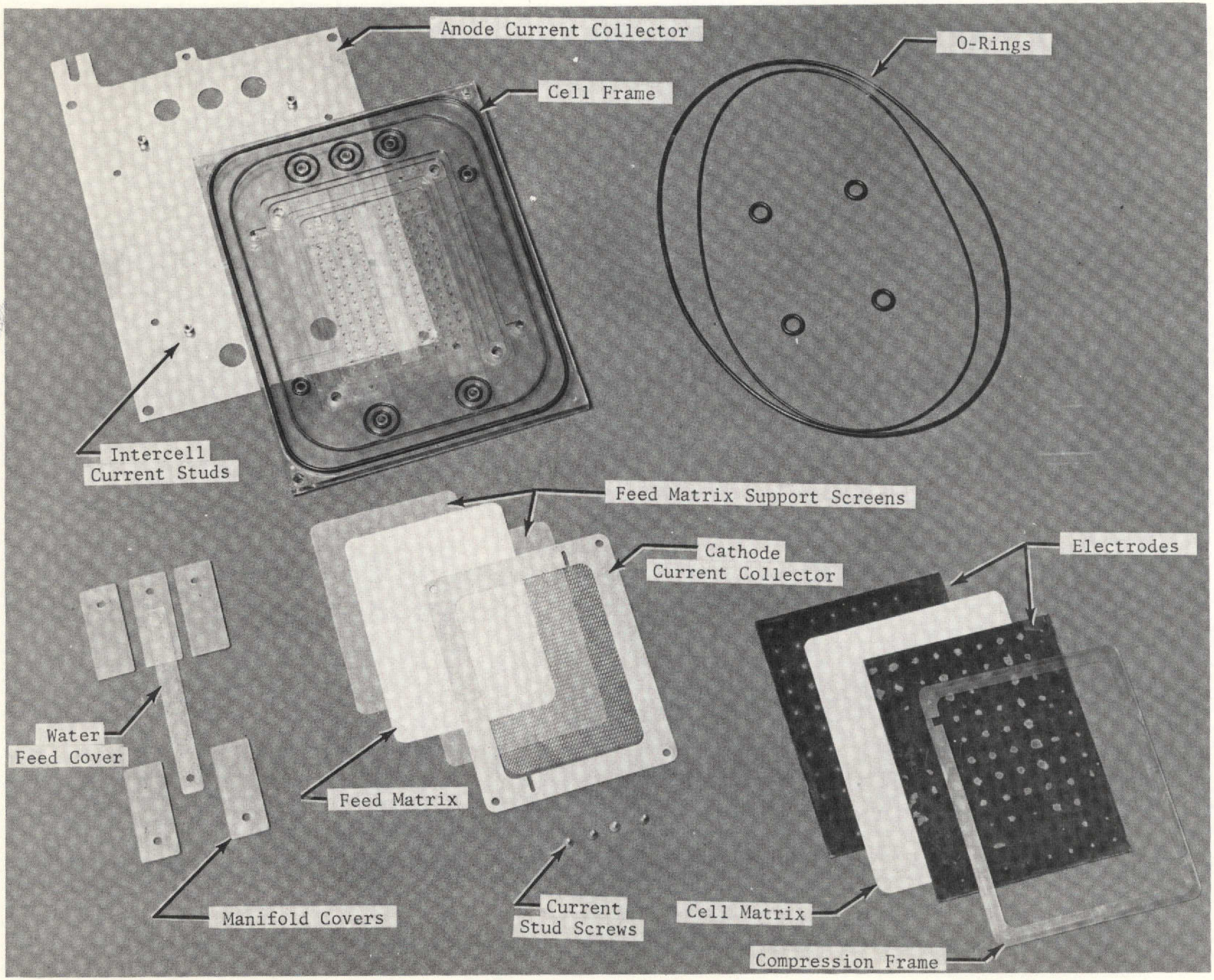


FIGURE 14 PARTS FOR ONE SFWEM CELL

Life Systems, Inc.

TABLE 3 SFWEM TEST SYSTEM SPECIFICATIONS

System Pressure Range, kN/m^2 (Psia)	103 to 2758 (15 to 400)
O_2 and H_2 Pressures above Water Pressure, kN/m^2 (Psid)	0 to 69 (0 to 10)
Module Current, A	0 to 50
Current Supply Compliance, V	0 to 20
Coolant Loop Control, K (F)	294 to 377 (70 to 220)
Process Water from Deionized Water Supply	As Required
Automatic Water Feed	As Required
Automatic Startup and Shutdown Sequencing with N_2 Purge	As Required
Manual Override of all System Valves	As Required

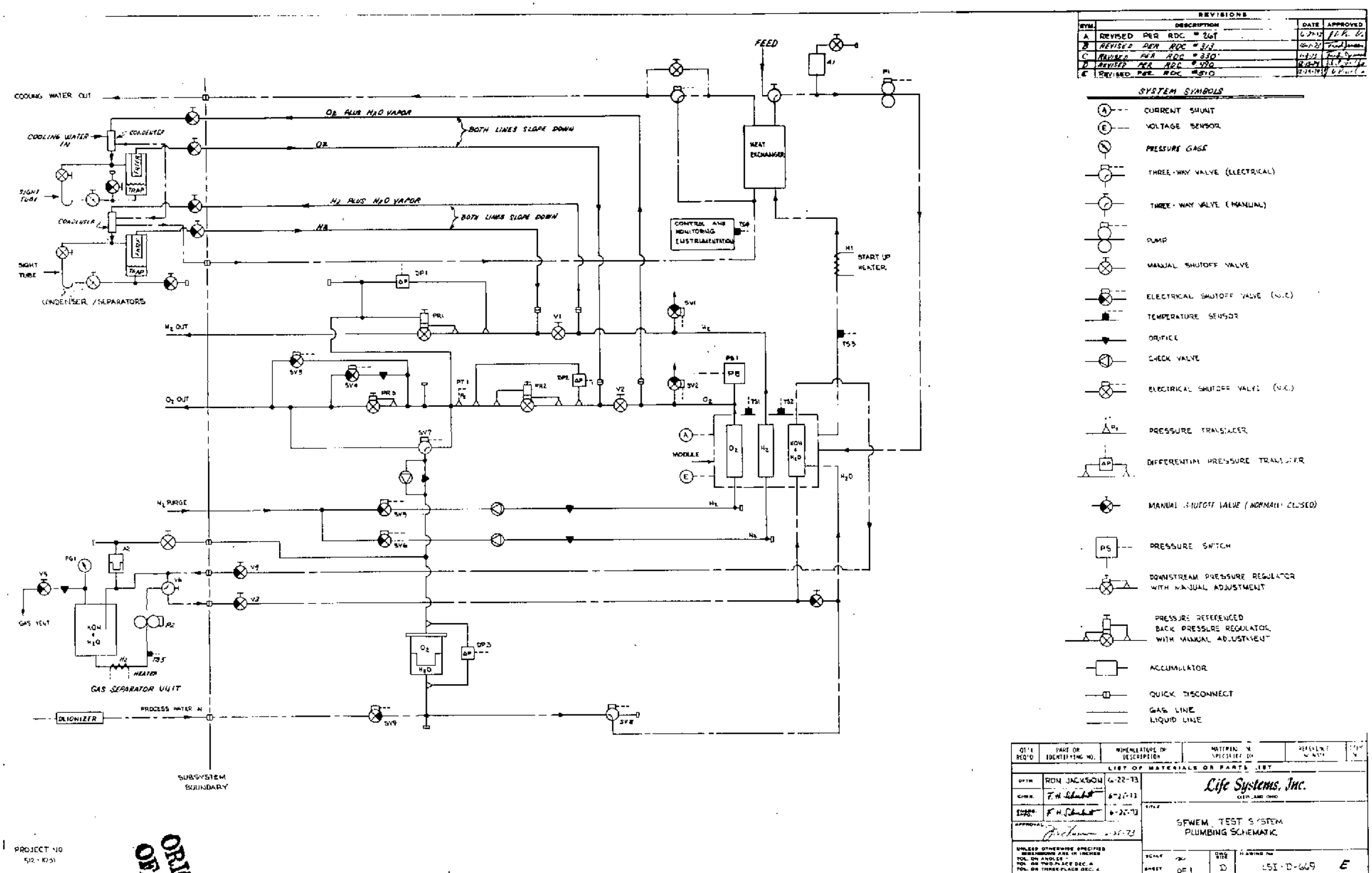


FIGURE 15 SFWEM TEST SYSTEM PLUMBING SCHEMATIC

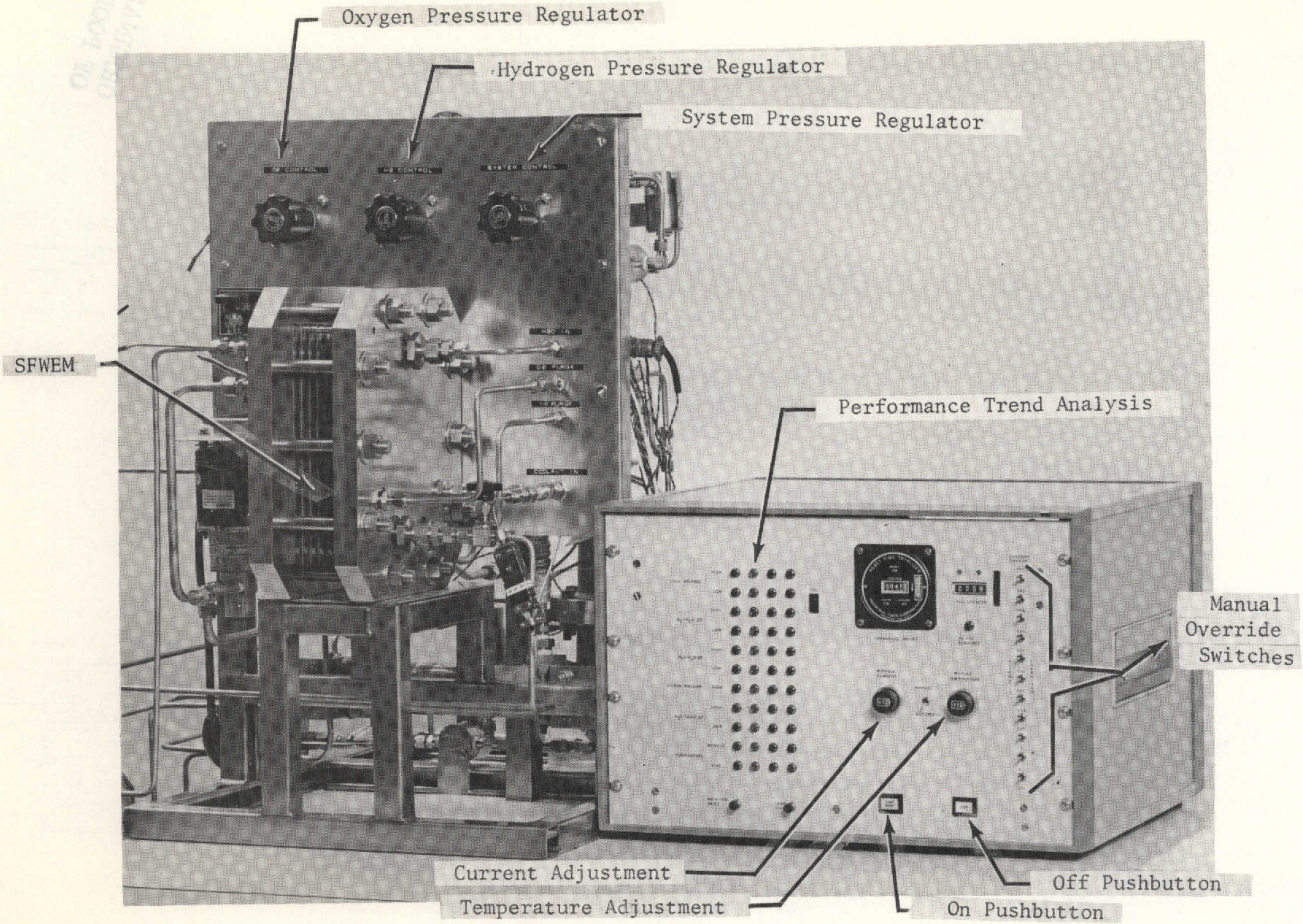


FIGURE 16 SFWEM TEST SYSTEM (STS)

Pressure Control. The SFWEM was designed to operate with the O_2 pressure above H_2 pressure and with the H_2 pressure above that of the fluid in the water feed cavities. These pressure differentials were required to prevent H_2 compartment flooding and to minimize the potential of H_2 leakage into the O_2 compartment.

Pressure control of the module fluids was accomplished as follows (see Figure 15). The manually-adjustable pressure regulator (PR3) established the feed water pressure. This pressure was transmitted to the water via O_2 in the water accumulator. This same water pressure level was used as a reference pressure for both regulators PR1 and PR2 to establish the H_2 pressure differential and O_2 pressure differential above that of the water.

Thermal Control. Thermal control of the module was achieved by circulating water through the individual coolant cavities of each cell of the SFWEM. A high flow of coolant was maintained to achieve a small temperature rise (1.7K (3F) nominal) in the coolant to minimize thermal gradients. The heat was rejected in a liquid-to-liquid heat exchanger by circulating a portion of the module coolant through the heat exchanger. This heat exchanger interfaced with the laboratory's coolant supply. An accumulator (A1) in the coolant loop provided for thermal expansion of the coolant fluid.

Feed Water Addition. Process water was supplied from the laboratory water supply. During operation, water was statically added from the pressure referenced accumulator to the SFWEM. This water accumulator was divided into a liquid and a gas compartment by a flexible diaphragm. The accumulator was automatically filled at fixed time intervals. The refilling time interval was based on the highest water consumption rate. During refilling of the accumulator, the module current was automatically reduced 85% to prevent the water feed compartment pressure from decreasing below tolerable levels.

Nitrogen Purge. Both the O_2 and N_2 compartments of each cell were capable of being purged with N_2. The flow of the N_2 was regulated by orifices upstream of the SFWEM. Purging was initiated during a shutdown sequence after the SFWEM had attained ambient pressure levels. A N_2 supply source of 30 psig was required. The flushing of both the O_2 and H_2 from the compartments was not only a safety feature but also prevented module pressure from going sub-atmospheric due to chemical recombination of the two gases after module shutdown or isolation.

Optional Operating Modes. Two optional operating modes were provided. They are operation with condenser/separators and operation with cyclic or continuous circulation of the fluid in the cells' water feed cavities. The two modes were used during design testing at conditions where condenser/separators are needed and to identify and quantify the possible presence of gases in the water feed.

The condenser/separators could be connected to the product gas lines by opening two hand valves and closing one other hand valve for each product gas line.

The liquid circulating loop interfaced with the manifolds of the SFWEM that connects to the water feed cavity's inlets and outlets. The circulating loop fluid could be preheated and its pressure regulated to match the SFWEM's operating conditions. During circulation, any gases present were trapped in a transparent gas separator. The internal volume of the separator was calibrated to quantify possible gas accumulation.

Electrical Subsystem

The electrical subsystem of the STS consisted of sensors and electronic components to provide control of SFWEM current, SFWEM operating temperature and system startup and shutdown sequences, as well as protective monitoring of system parameters.

The control and monitor instrumentation used Life Systems' standard printed circuit (PC) cards. The total test system required 19 PC cards, 14 for monitoring and five for control circuits. All monitoring cards were similar to previously built and tested cards[12] while the five control cards were designed specifically for the SFWEM test system. Table 4 is a detailed listing of the PC cards needed, indicating the card number, name, function, quantity, and number of performance trend levels.

SFWEM Current Control. The current control converted DC input power to a constant, adjustable DC current which was used to power the SFWEM. Figure 17 is a block diagram of this control. The DC input power was sent to a solid state power switch which was turned on and off at a fixed rate with a variable duty cycle as determined by the pulse width modulator circuit. The chopped power was then filtered to produce a smooth DC current and was passed through a current measuring shunt to the SFWEM. The shunt signal goes to the control logic where it was compared with a current set signal (external or internal). The difference between these two signals was used to operate the pulse width modulator until the current signal from the shunt and the current set signal were equal. Thus, the SFWEM current tracked the current set signal.

The use of a switching regulator resulted in a very efficient system with a power conversion efficiency of 85%. The current control system for the SFWEM delivered from 0 to 50 amps to a cell or module load with a voltage compliance of 0 to 20 volts.

SFWEM Temperature Control. The temperature control maintained the SFWEM at a predetermined temperature by actuating a three-way solenoid valve which caused the liquid coolant to bypass or flow through a liquid-to-liquid heat exchanger. Figure 18 is a block diagram of this control system.

The SFWEM temperature was monitored by means of a thermistor type temperature sensor. This signal was sent to the temperature control logic where it was compared with a manual temperature set signal. The difference between these two signals was used to operate the valve driver circuit which controls the position of the valve.

Sequence Control Logic. The STS had two operating modes, STOP and ON, and one nonoperating mode during which the system power was totally removed. The system sequence control logic controlled the transitions during the STOP to ON

TABLE 4 STS PC CARD LIST

No.	Location in System	Name	Function	Trend Level (a)	Quantity Old (b)	Quantity New (c)
A7	A	Tank Fill Logic	Controls water tank filling	NA (d)		1
A8	B	On/Shutdown Logic	Controls startup and shutdown sequences	NA		1
A9	C	Purge Fill Sequence	Controls N_2 purge sequence	NA		1
A10	D	Current Control Logic	Provide PWM (e) to power switch	NA		1
A11	E	Diverter Valve (Temp.) Control	Provide signal to operate diverter valve for temp. control	NA		1
B2	F	Temperature Monitor	Monitor high module temp.	4	1	
B2	G	Temperature Monitor	Monitor high electronic temp.	4	1	
B6	H	Transducer Monitor	Monitor high water tank ΔP	4	1	
B6	I	Transducer Monitor	Monitor low water tank ΔP	4	1	
B6	Q	Transducer Monitor	Monitor high O_2-water ΔP	4	1	
B6	R	Transducer Monitor	Monitor low O_2-water ΔP	4	1	
B6	S	Transducer Monitor	Monitor high H_2-water ΔP	4	1	
B6	T	Transducer Monitor	Monitor low H_2-water ΔP	4	1	
B6	U	Transducer Monitor	Monitor high water (system) pressure	4	1	
B7	N	Voltage Level Monitor	Monitor high cell voltage	4	1	
B7	O	Voltage Level Monitor	Monitor low cell voltage	4	1	
B9	L	Scan Control Logic	Operate scan relays on B10	NA	1	
B10	M	Scan Relays	Scan module cell voltage	NA	1	
B11	P	Flash Oscillator/ PSSI Logic	Flashing oscillator and status summary logic	NA	1	
			Totals		14	5

(a) Four levels include trend and shutdown protection.
(b) Previously designed, built, and tested.
(c) New or modified designs.
(d) NA = Not Applicable
(e) PWM = Pulse Width Modulation

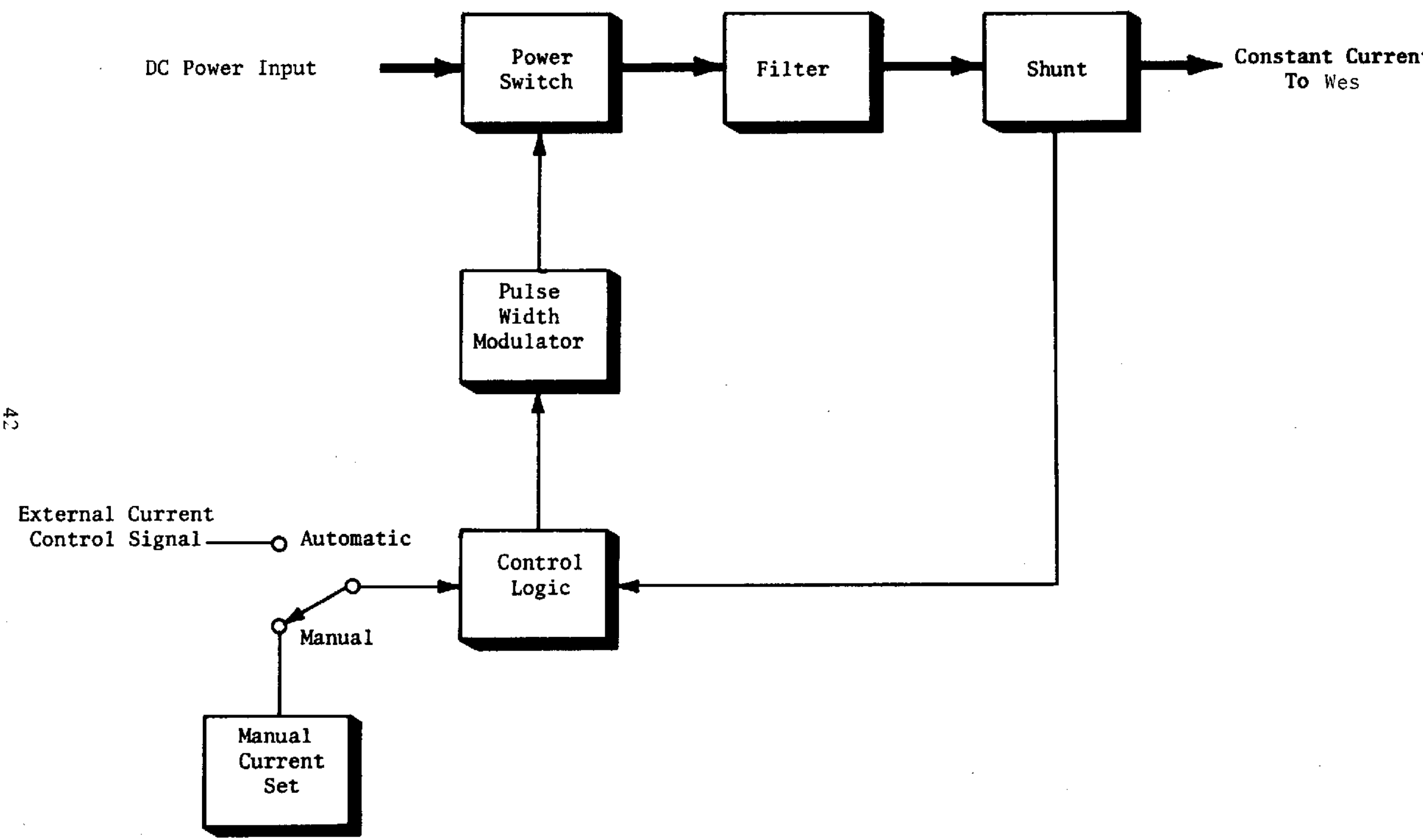


FIGURE 17 SFWEM CURRENT CONTROL BLOCK DIAGRAM

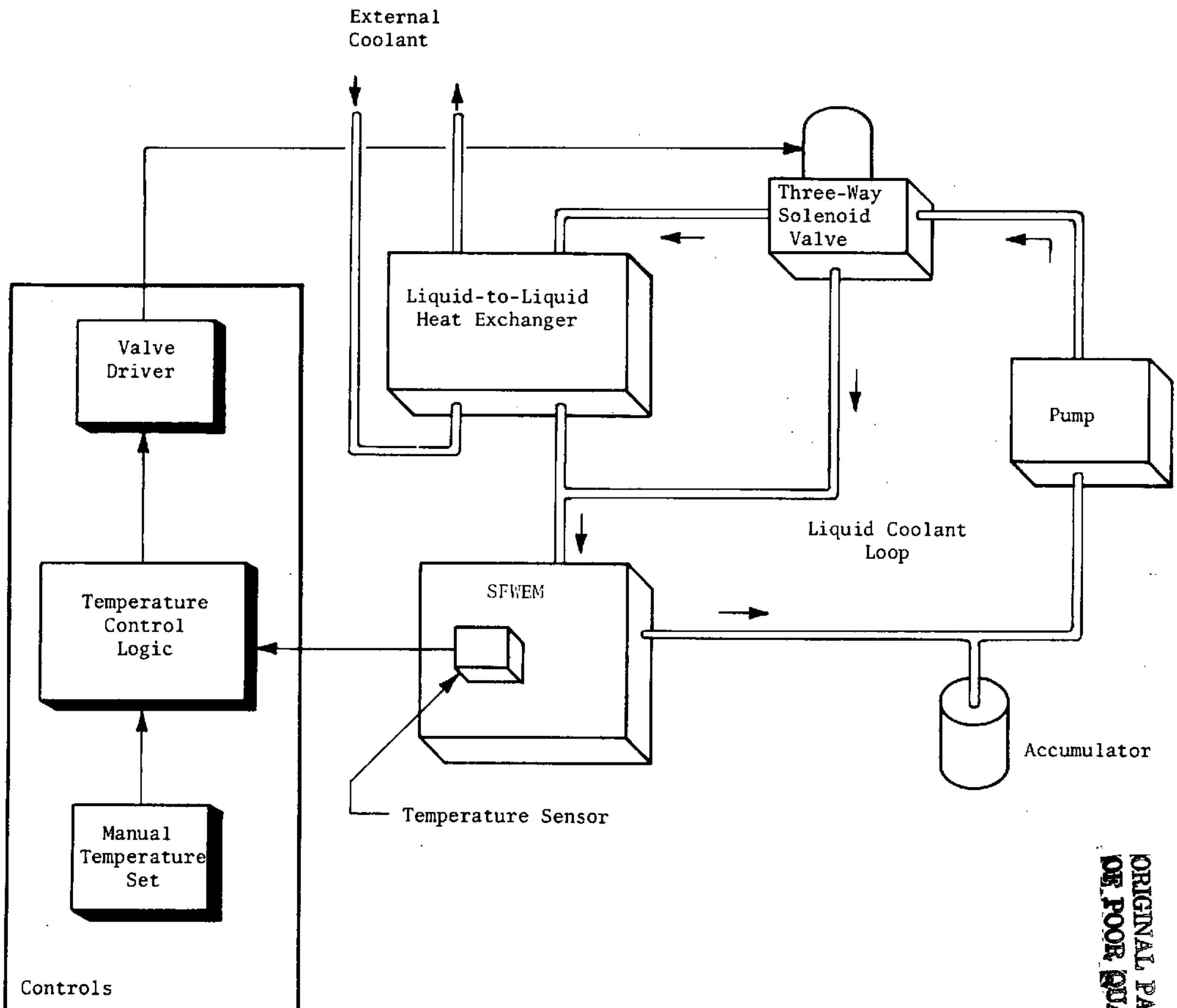


FIGURE 18 SFWEM TEMPERATURE CONTROL BLOCK DIAGRAM

and ON to STOP sequences. This logic also controlled the water accumulator fill sequence based on an elapsed time set at about six-hour intervals. Detailed descriptions of the sequential steps performed during the mode transitions (Power On, Startup, Water Tank Fill, and Shutdown) are presented in Appendix 1.

Monitor Instrumentation. The monitor instrumentation for the test system of the SFWEM consisted of circuits previously developed for use in other life support systems. A basic element in this instrumentation was a PC card which contained signal conditioners, level detectors, storage, lamp drivers, and logic, along with built-in test features as shown in the block diagram of Figure 19.

The typical monitoring card accepted a sensor input signal and conditioned it to the standard 0 to 5V DC level. The conditioned signal was available for analog readout by plug-in test equipment. The 0 to 5V DC signal was digitized on the card by two or three level detectors into three or four ranges, depending on the parameter being processed. The third level (entering into the fourth range) was the shutdown level. The logic on the card allowed both the present level and the previously attained highest level to be displayed simultaneously on indicator lamps. A reset input allowed the stored information to be removed when desired. Also, a lamp test input allowed the lamps connected to the card to be checked. The present level signals from the cards were connected to a status summary logic circuit which could operate a system status summary indicator displaying the highest present level from all monitor instrumentation cards.

A scanning system was required to monitor individual cell voltages from the SFWEM. Card Type B10 (see Table 4) contains the relays for scanning the cell voltages. This card was operated from Card Type B9 which contained the logic to drive the relays and also the circuits necessary to drive the cell counter panel readout.

Display and Control Panel. All electronic circuits and controls, including the PC card rack were housed within a single container 48 cm (19 in) wide, 30 cm (12 in) high, and 41 cm (16 in) deep, as shown in Figure 20. Electrical connectors were used wherever possible between components of the test system and the controls themselves. The front panel of this container is a display and control panel which contains performance trend and fault analysis indicator lights, cell counter readout, control potentiometers, pushbuttons and toggle switches. During normal operation the trend and fault analysis indicators will have all green lamps lit. As a parameter moves out of its normal range it will first light the amber, then the flashing red, and finally the red indicator. Simultaneously, with lighting the red indicator, an automatic shutdown signal will be sent to the sequence control logic. If the parameter returns to a lower level, the highest level having been attained will be indicated as well as the present, real time level.

Parametric Readout. Figure 21 shows the STS parametric readout which allowed reading of all system parameters. This readout had two switches to allow selection of the parameter to be read on the meter. It was connected to the STS electronic cabinet by a cable and connector as shown.

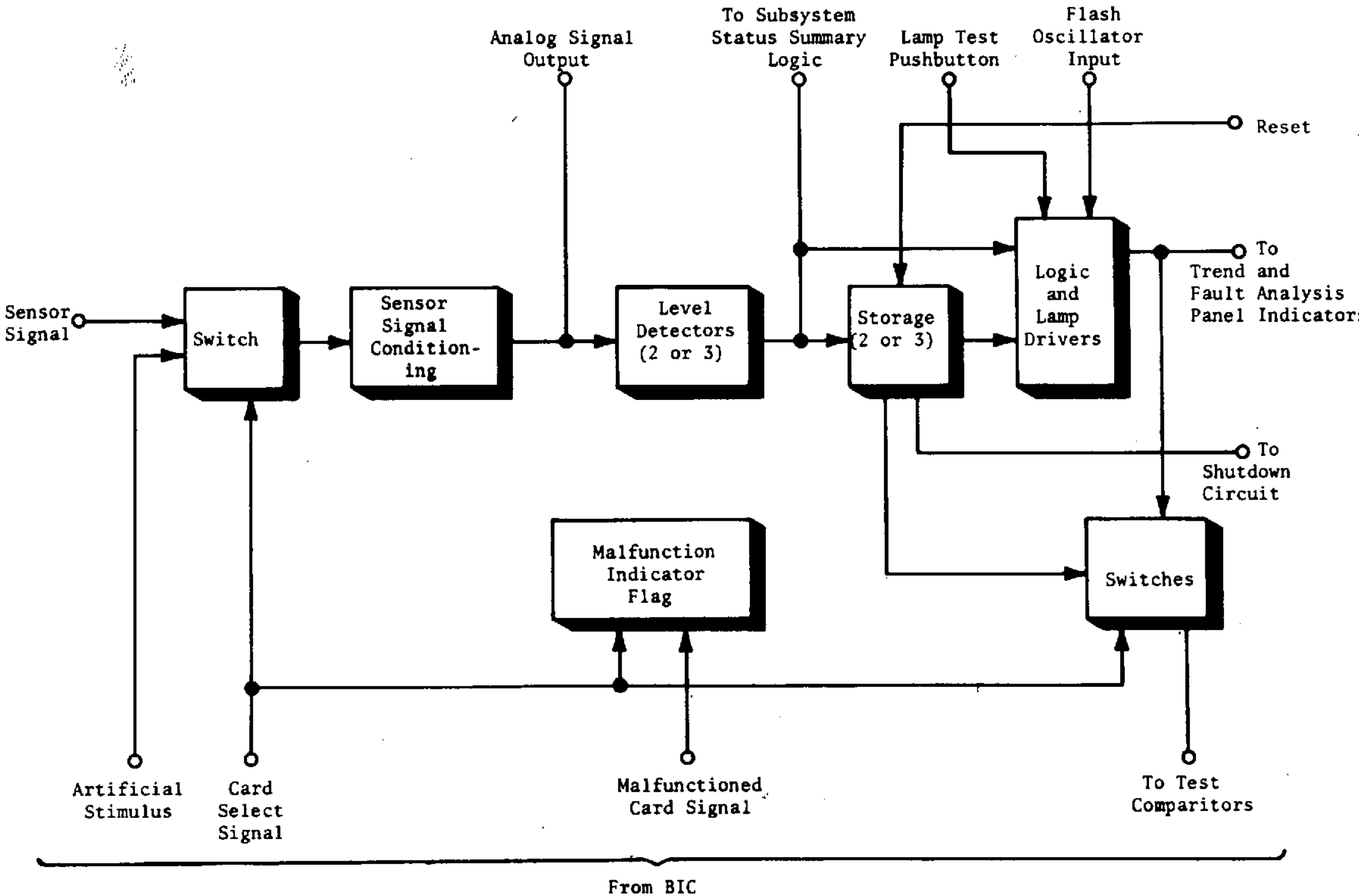


FIGURE 19 MONITORING INSTRUMENTATION PC CARD BLOCK DIAGRAM

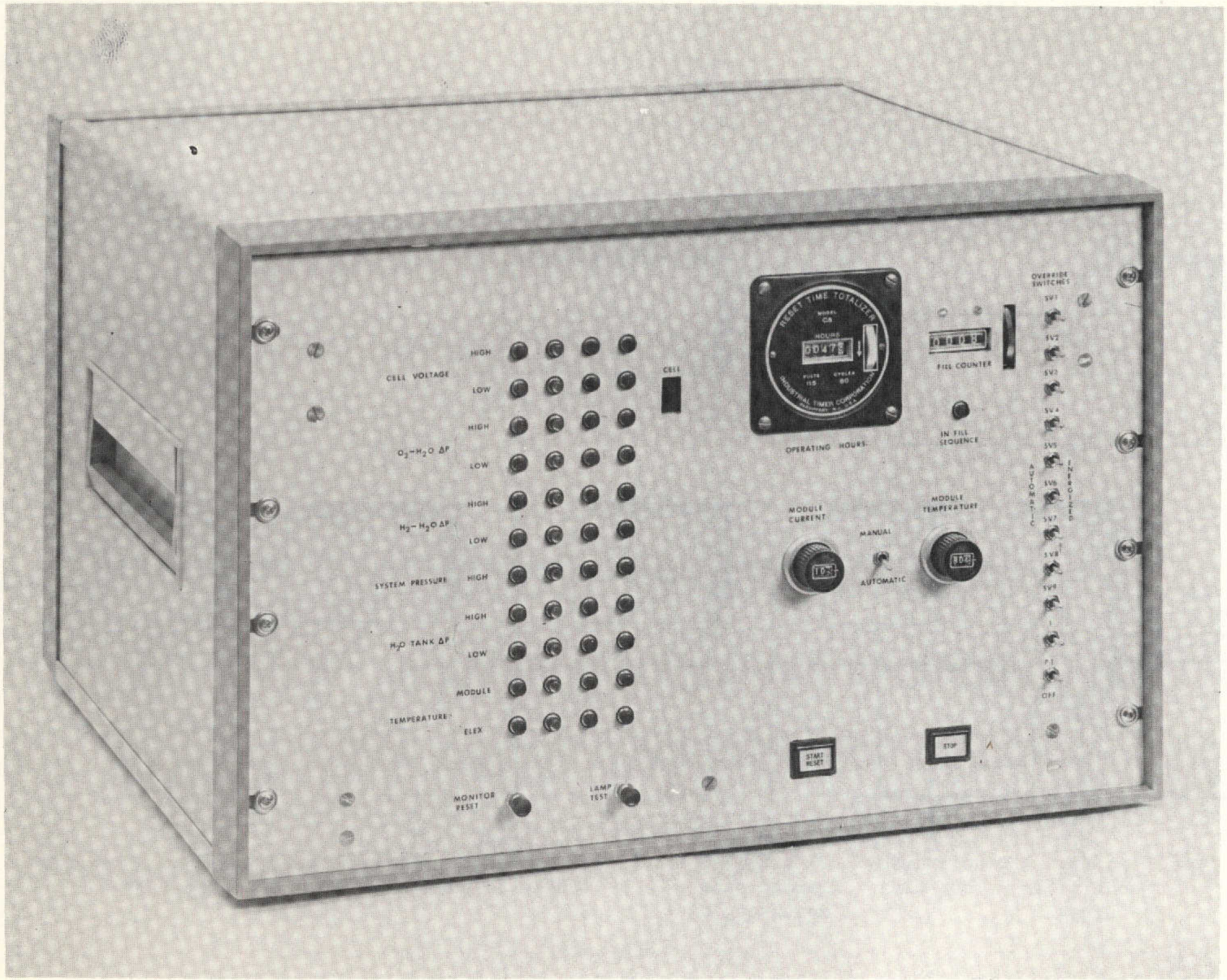


FIGURE 20 STS ELECTRONIC CONTROL AND MONITORING INSTRUMENTATION

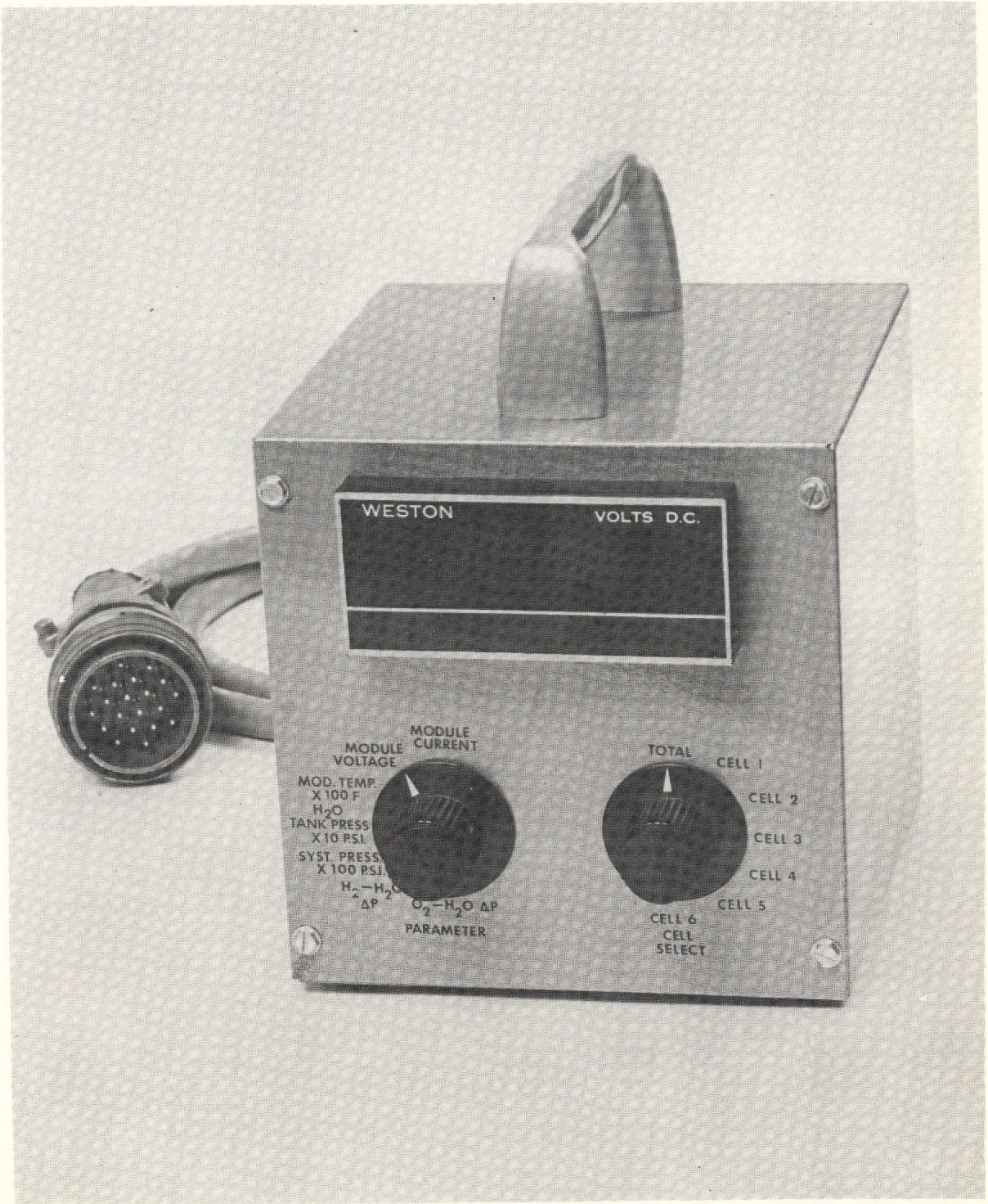


FIGURE 21 STS PARAMETER READOUT

Sensors. There were nine sensors used in the STS. Table 5 lists these sensors and their uses. The three differential pressure transducers and the water pressure transducer are bridge transducers with internal conditioning circuts.

Three stainless steel-sheathed thermistor temperature sensors were included in the system. One measured the tempeature of the control and monitoring instrumentation circuits and two measured module temperature, one for control and one for monitoring. The final sensors in the system were two thermocouples, one connected to the liquid coolant loop and the other one connected to the gas separator circulating loop. These sensors were connected to external monitoring equipment, only, and were not used as part of the system monitoring or control instrumentation.

Condenser Separators

Two water-cooled condenser/separator assemblies were available in the GSA to allow operating the SFWEM during the test program at off-design conditions. Manually operated valves allowed the insertion or removal of the condenser/separators from the O_2 and H_2 producing streams. During normal system operation these units are not used. For testing at off-design conditions (which produce high humidity levels, i.e., high temperature, low pressure, low electrolyte concentration, in the product gases) these units would be switched into place.

Gas Separator Unit

The GSU was designed for location outside of the STS (Figure 15) since it was not needed at design operating conditions. It consisted of a circulating pump, accumulator, a gas separator tank, and a variety of hand valves and gauges. The GSU served to identify if gases were present in the SFWEM water feed compartments and in what quantities. The GSU was connected to the STS by a quick disconnect fitting and used hand valves to control its operation. When the GSU is circulating fluid through the feed compartments of the module, any gas contained in the feed system was trapped in the gas separator tank. This tank is transparent and the amount of gas can be measured. The GSU is capable of circulating water feed compartment fluids through the six cells of the module at a pressure and temperature equal to the module's operating valves. This is important, since any perturbations in these parameters during the circulating mode could impair the accuracy of the gas measurement.

Fluid and Electrical Supplies

The STS required N_2 at a pressure of 310 kN/m^2 (45 psia) for purging the H_2 and O_2 lines of the STS and SFWEM during a shutdown sequence.

Cooling water at 277 to 289K (40 to 60F) is required to remove the SFWEM heat via the heat exchanger in the STS. When the condenser/separators are used they also require cooling water.

The GSA also supplied the water required for electrolysis at a rate of 0.725 cm^3/min (2.30 lb/day) when the SFWEM was operating at design conditions. This water is city supply water which has been processed through a deionizer column.

TABLE 5 SFWEM TEST SYSTEM SENSORS

No.[a]	Parameter	Range	Type
DP1	H_2-Water Pressure Differential, kN/m^2 (Psid)	0 to ±69 (0 to ±10)	Bridge Transducer
DP2	O_2-Water Pressure Differential, kN/m^2 (Psid)	0 to ±69 (0 to ±10)	Bridge Transducer
DP3	Water Tank Pressure Differential, kN/m^2 (Psid)	0 to ±207 (0 to ±30)	Bridge Transducer
PT1	Water Pressure, kN/m^2 (Psia)	0 to 3448 (0 to 500)	Bridge Transducer
TS1	Module Temperature, K (F)	294 to 377 (70 to 220)	Thermistor, 100KΩ
TS2	Module Temperature, K (F)	294 to 377 (70 to 220)	Thermistor, 100KΩ
TS3	Liquid Coolant Temperature, K (F)	294 to 377 (70 to 220)	Thermocouple, Type J
TS4	Instrumentation Temperature, K (F)	294 to 377 (70 to 220)	Thermistor, 100KΩ
TS5	Gas Separator Temperature, K (F)	204 to 377 (70 to 220)	Thermocouple, Type J

(a) Per test system schematic, Figure 15.

The electrical requirements of the STS are 24 to 32 VDC at 286 watts and 115 VAC, 400 Hz at 100 watts when the SFWEM was operating at design conditions. Manual control for module current and temperature were contained on this panel as well as the pushbuttons to send the system to the two operating modes, i.e., STOP and ON. Included on the panel are pushbuttons to allow testing of all indicator lamps and resetting of stored information contained on the trend analysis lamps, an indicator to show when the water tank is being filled, and switches to allow the operation of all system functions manually.

STATIC FEED WATER ELECTROLYSIS TESTING

The objectives of the testing were to (1) prove the SFWEM design concept at the single cell level, (2) experimentally characterize the SFWEM performance, and (3) evaluate new electrodes and matrices. To accomplish these objectives a four-part test program was completed:

1. The SFWEM test system checkout and shakedown tests.

2. Module Design Verification Single Cell Tests.

3. The SFWEM testing (shakedown, parametric, and 90-day endurance).

4. Component evaluation single cell tests.

SFWEM Test System Checkout Tests

After the STS was assembled and all components had been installed, a series of checkout tests were performed. These tests were designed to ensure that the STS performed to its specifications, contained no leaks and was ready for SFWEM use. During this testing several leaking fittings were identified and replaced. A faulty system pressure transducer was also discovered and returned to the vendor for correction.

Module Design Verification Single Cell Tests

These tests were performed to verify the integrity of the SFWEM design before beginning fabrication of the six-cell module. The tests consisted of operating the cell at ambient temperature at current densities up to 1076 mA/cm^2 (1000 ASF), and pressures up to 1724 kN/m^2 (250 psia).

Effect of Current Density

The single cell was operated at current densities up to 1076 mA/cm^2 (1000 ASF) to verify that the electrical and electrochemical performance was as designed. Figure 22 shows the results of the current density test. The low slope in the curve obtained indicates low IR losses, verifying that good electrical contact and connections between the electrodes and the current collectors and between adjacent cells was achieved with the SFWEM design. The capability of the cell to sustain operation at the high current density levels shown indicated that the design objective of decreased resistance to water feed and increased electrode-matrix-electrode tolerance to electrolyte volume fluctuations had been attained.

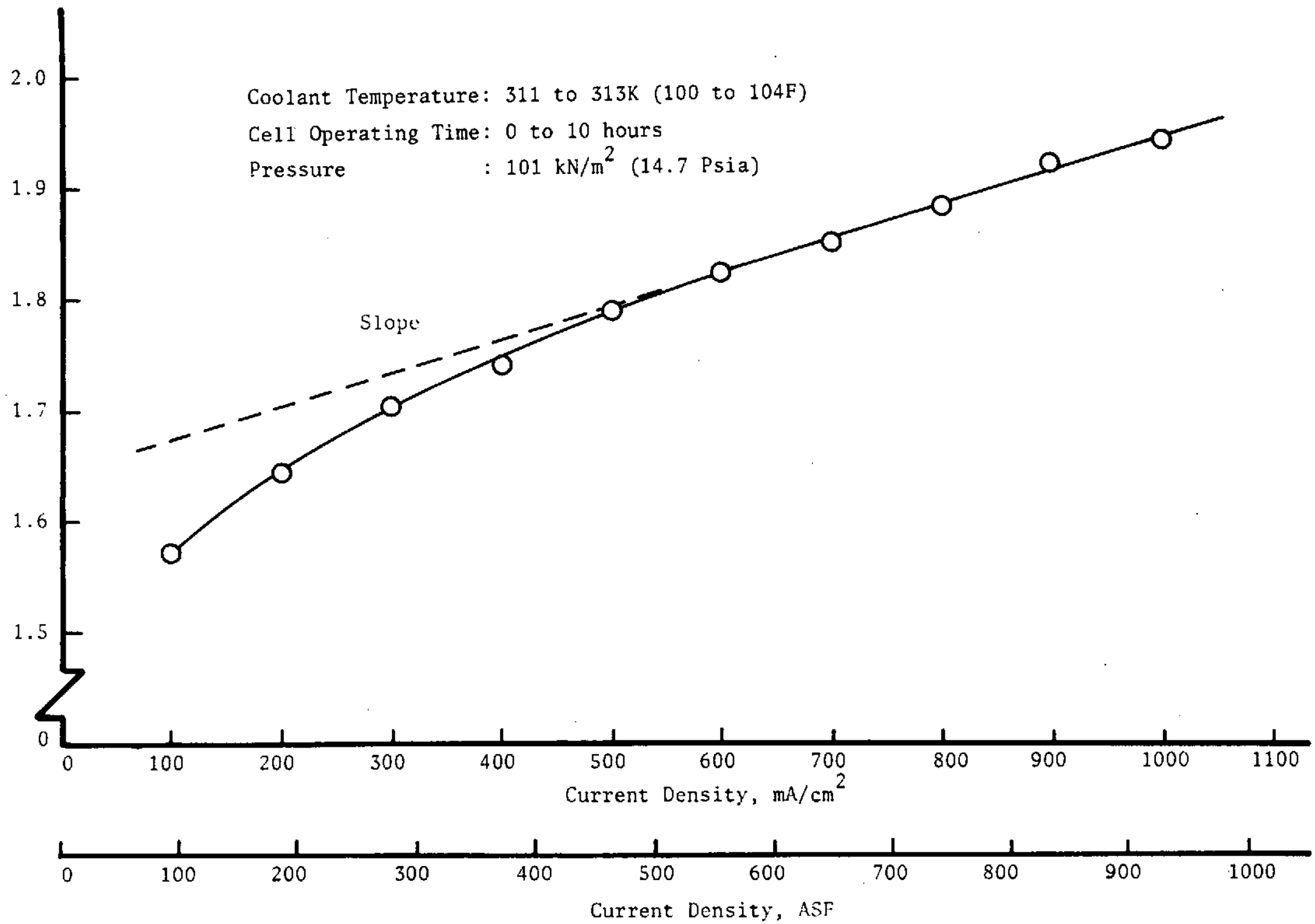


FIGURE 22 EFFECT OF CURRENT DENSITY ON CELL VOLTAGE

Effect of Pressure

The pressure test was used to evaluate the mechanical integrity and performance of the SFWEM design. Figure 23 shows the results of the pressure tests. The data demonstrated that the mechanical construction was sound and that electrical connectors and contacts (electrodes-to-matrix-to-current collectors) were held secure at the elevated pressures. The increase in the cell voltage at an operating pressure of 1724 kN/m^2 (250 psia) over that observed for ambient pressure operation is as expected. This increase was primarily due to the diffusion rate of water vapor through the H_2 cavity which is inversely proportional to the absolute pressure level. Any decrease in the rate of water transport resulted in a decrease in the cell matrix electrolyte volume accompanied by an increase in electrolyte concentration. Both factors adversely affect cell voltage.

The increased voltage required to produce a H_2 molecule at the higher pressure has little effect over the range in pressures investigated.[3]

SFWEM Testing

Following integration of the SFWEM into the STS, an integrated SFWEM-test facility shakedown test was performed followed by performance characterization tests consisting of a series of parametric tests and a 90-day endurance test.

SFWEM-Test Facility Shakedown Test

The objective of the SFWEM-test facility shakedown test was to eliminate infancy-type failures common to first-time-operation of integrated test setups. During this test failures of the two backpressure regulators occurred. The causes of the failures were traced to improper assembly at the vendor's plant. Following repair and adjustments to the regulators, the shakedown testing was successfully completed by demonstrating eight hours of continuous operation.

Module Parametric Tests

A series of parametric tests were performed to experimentally characterize SFWEM performance as a function of pertinent operating parameters. Module and cell voltages were to be investigated as a function of (a) current density (323 mA/m^2 (300 ASF)) and operating temperature (ambient to 366K (200F)), (b) operating pressure (ambient to 1724 kN/m^2 (250 psia)), (c) process fluid pressure differential (34 kN/m^2 (5 psid)), and (d) cyclic on-off operation, six hours per day for a five day period. Throughout the testing emphasis was placed on observing any factors that resulted in minimizing cell voltage, feed water degassing requirements and aerosol formation.

Effects of Current Density and Temperature. The combined effects of current density over a range of 108 to 538 mA/cm^2 (100500 ASF) and operating temperature from ambient to 366K (200F) on the performance of the SFWEM were investigated. The results are shown in Figure 24. The data shows that the cell voltage decreases for increases in temperature or decreases in current density. The results indicated an average 2.6 mV/K (1.4 mV/F) decrease in cell voltage over the range

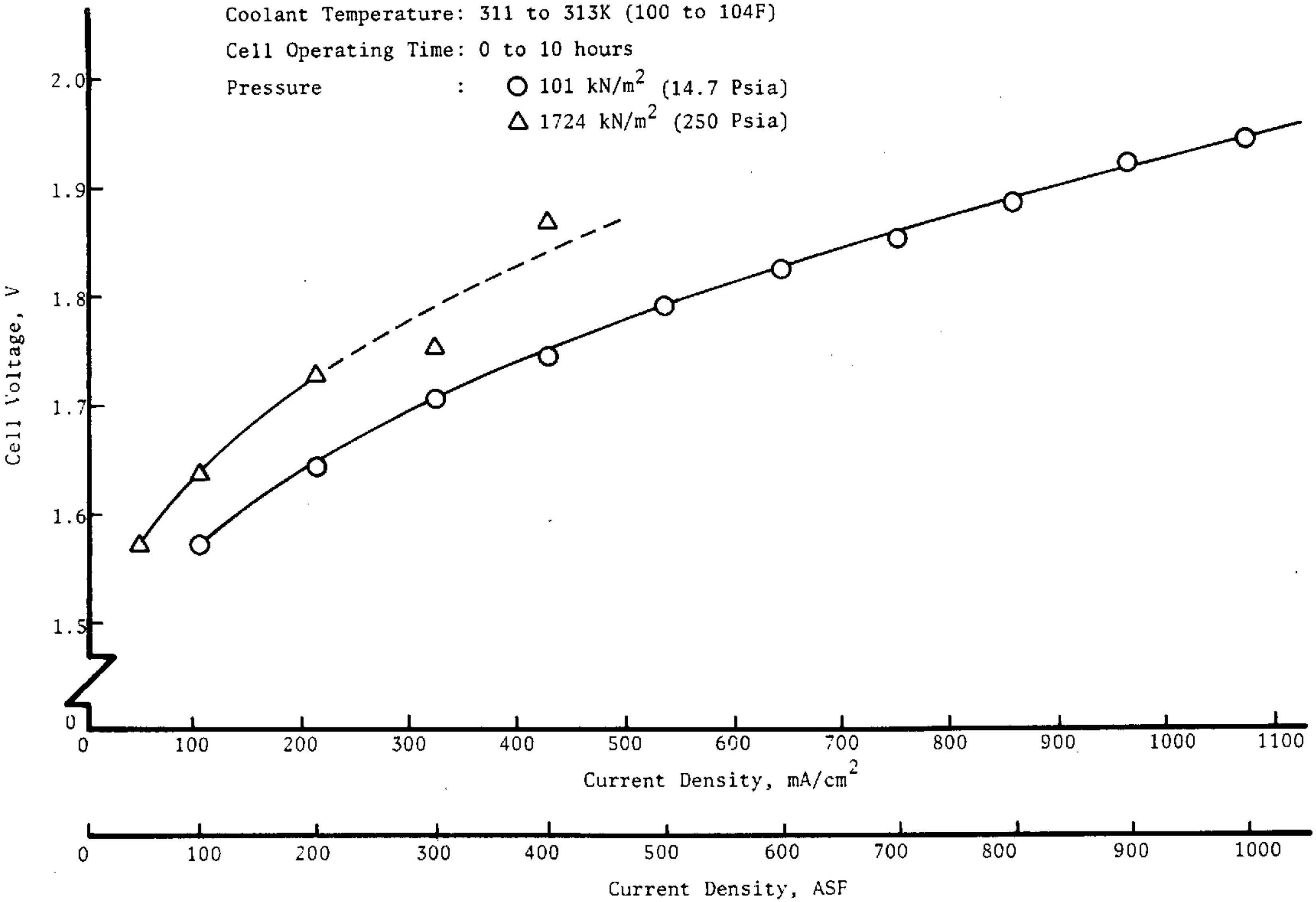


FIGURE 23 EFFECT OF PRESSURE ON CELL VOLTAGE

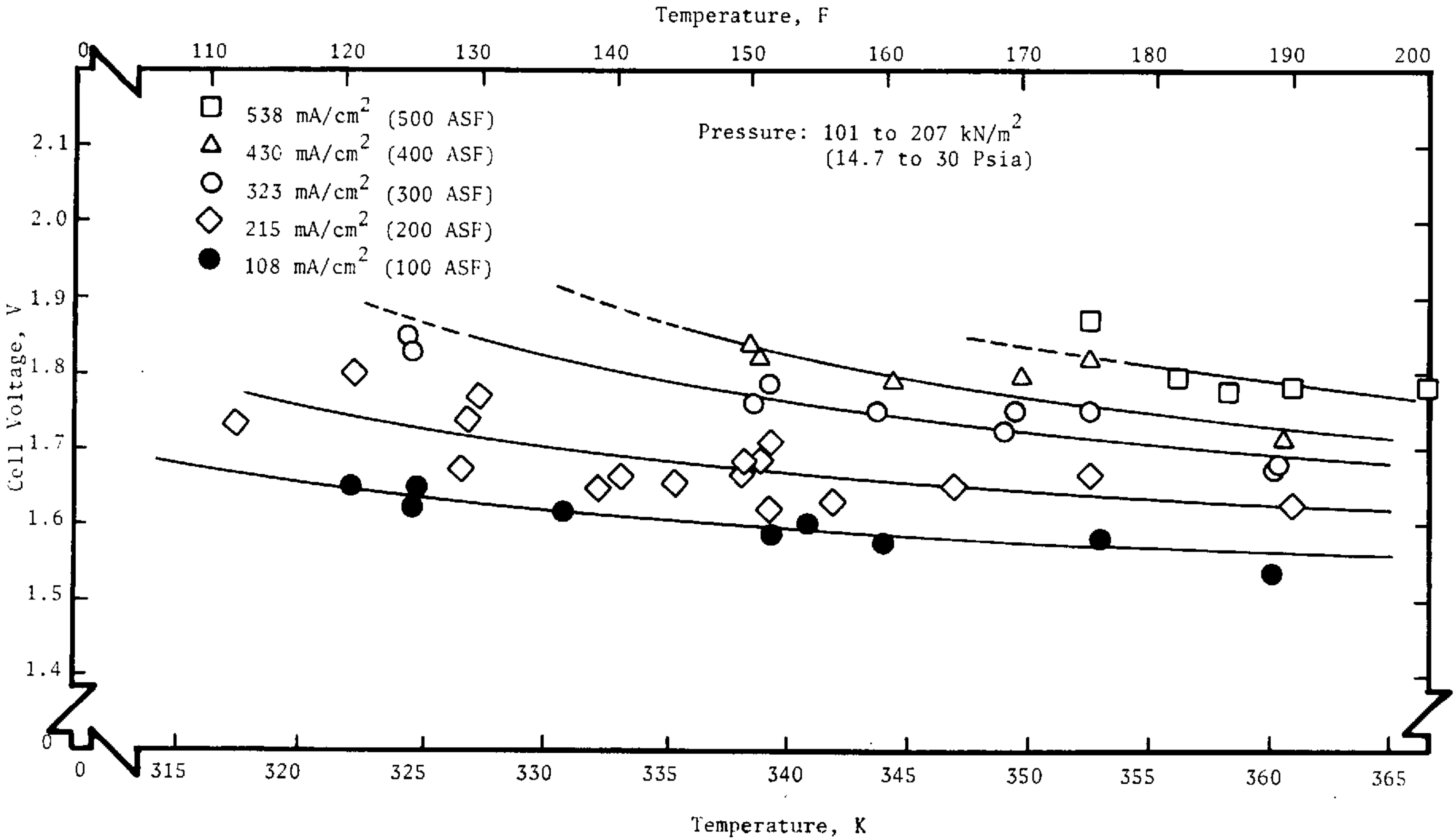


FIGURE 24 EFFECTS OF CURRENT DENSITY AND TEMPERATURE ON SFWEM PERFORMANCE

in operating parameters investigated. Transition points from the solid lines to dashed lines (for the various current densities) in Figure 24 indicate the projected temperature dependent operational limits of the SFWEM for the specific current density levels indicated. The capability of the module to perform in excess of the projected 323 mA/cm^2 (300 ASF) by demonstrating operation at 538 mA/cm^2 (500 ASF) showed that the design-related objectives were successfully met.

Effects of Operating Pressure. An operating pressure test was completed on the SFWEM which covered the range of ambient to 1724 kN/m^2 (250 psia). Figure 25 shows that the SFWEM voltage increased at an average rate of 0.6 mV per kN/m^2 (4.1 mV per psia). The reason for this increase was discussed in the Module Design Verification Single Cell Test section.

Effects of Process Fluid Pressure Differentials. The SFWEM was designed and run with the O_2 pressure greater than the H_2 pressure. This was done to avoid any possibility of H_2 leaking into the O_2 cavity. SFWEM performance actually improved, as shown in Figure 26, when the H_2 pressure was greater than the O_2 pressure. The data shows a 0.42V increase in module voltage (70 mV per average cell) as the O_2 to H_2 differential pressure is varied from -34 kN/m^2 (-5 psid) to +34 kN/m^2 (+5 psid).

Effects of Cyclic Operation. During the last five days of the parametric test program the effects of cyclic operation on the performance of the SFWEM was investigated. For about six hours each day for five days the current was cycled on and off. Each cycle consisted of 58 minutes with the current on, followed by 36 minutes with the current off simulating the sunlit/shade cycles of a near-earth orbit. This type of operation would allow the O_2 Generating Subsystem to use cheaper power (122 kg/kw (270 lb/kw) for sunlit orbit, only, versus 268 kg/kw (590 lb/kw) for continuous operation).

During the current off portions of the cycle the gas pressures in the STS were held at their operating levels by a regulated N_2 source. When the current is turned off, recombination begins in the module. For the particular SFWEM design this caused the H_2 pressure to drop below the O_2 and system pressure by too great an amount. Excess pressure differentials can be detrimental to the SFWEM so, therefore, N_2 pressure was used to keep the pressures at the desired levels.

The performance of the SFWEM was improved by the cyclic test. The module voltage dropped by 0.12V for an average decrease in cell voltage of 20 mV. This would be equivalent to a savings in total equivalent weight of 1.0 kg (2.2 lb) based on the O_2 requirements of a six-man crew aboard a near-earth orbit spacecraft. The total savings in power source weight when the effects of using the cheaper power is included exceeds 185 kg (405 lb) for a six-man system.

Endurance Testing

Endurance testing of the SFWEM immediately followed completion of the parametric tests. Figure 27 shows the stack voltage of the six cell module, maximum and minimum cell voltage, and current density as a function of time. Table 7 lists

Temperature: 339 to 344K (150 to 160F)

Current Density: 215 mA/cm^2 (200 ASF)

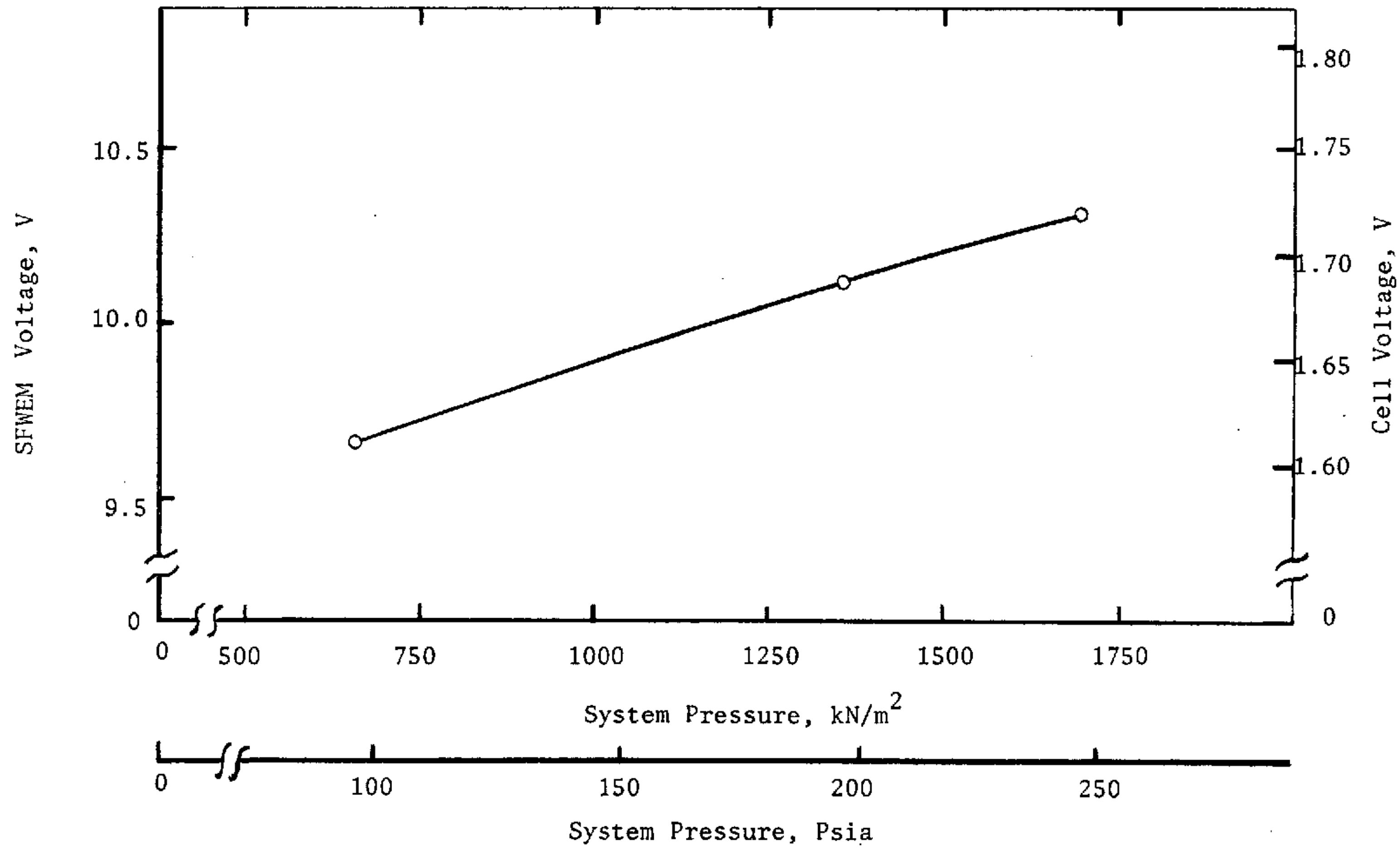


FIGURE 25 EFFECT OF PRESSURE ON SFWEM PERFORMANCE

Current Density: 215 mA/cm^2 (200 ASF)
Temperature : 339 to 344K (150 to 160F)
Pressure : 1034 kN/m^2 (150 Psia)

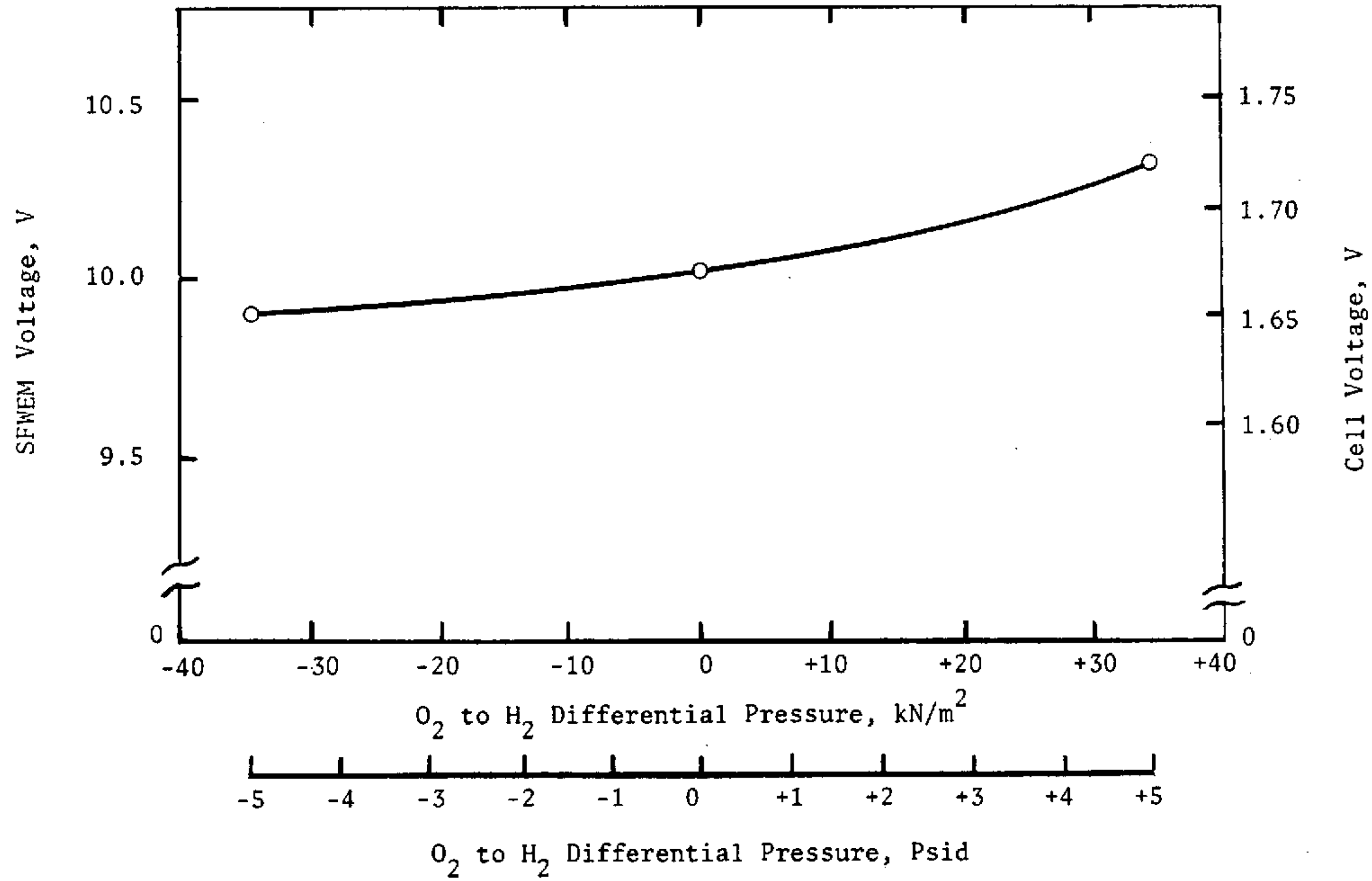
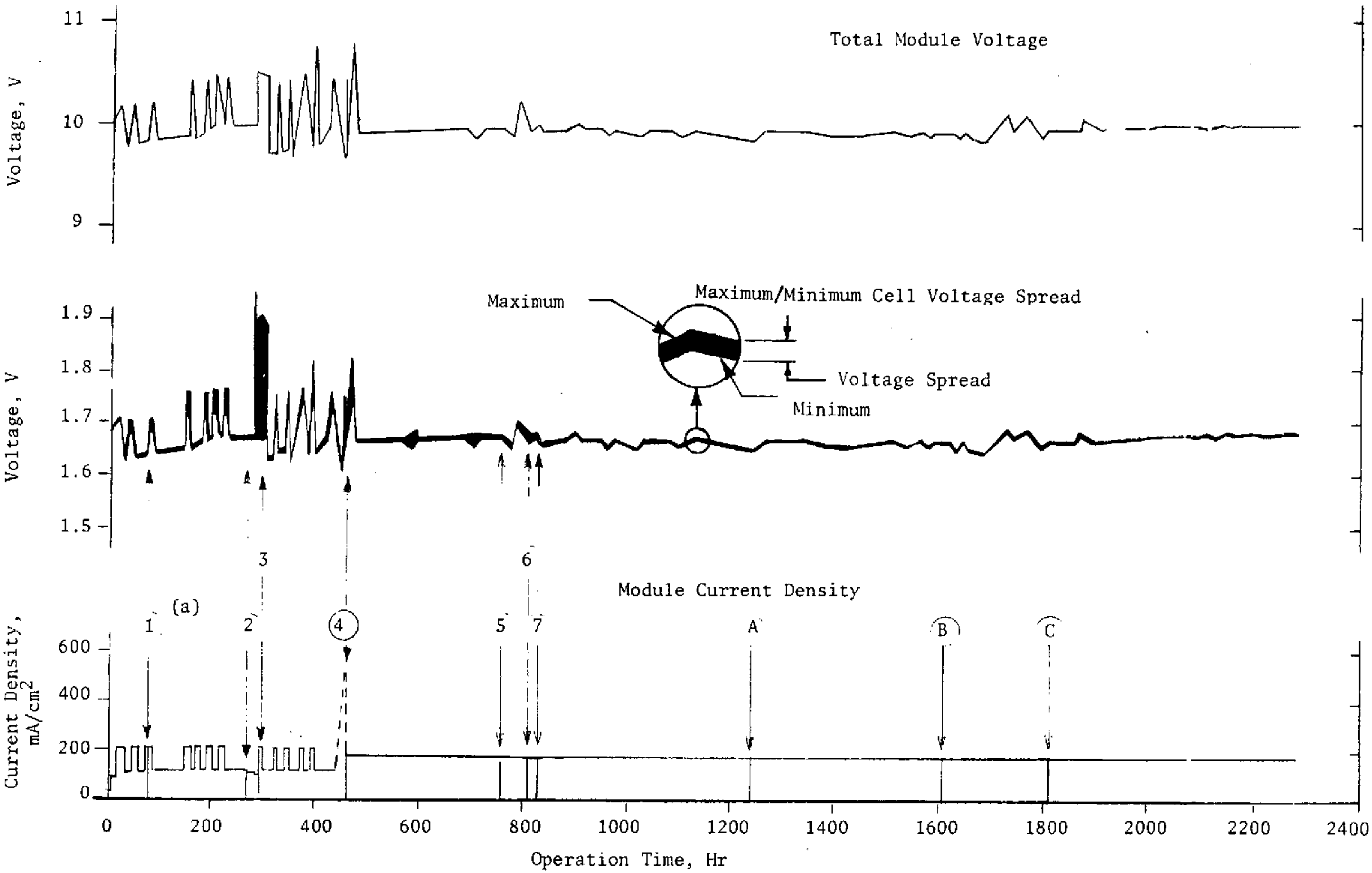


FIGURE 26 EFFECT OF O_2 to H_2 DIFFERENTIAL PRESSURE ON SFWEM PERFORMANCE



(a) See Table 6 for explanation of items noted within the circles.

FIGURE 27 SFWEM 90-DAY ENDURANCE TEST

TABLE 6 90-DAY ENDURANCE TEST NOTES

Shutdowns

1 Operator error during data taking

2 High cell voltage

3 High O_2-Water ΔP

4 High cell voltage

5 Low cell voltage

6 Low cell voltage

7 High cell voltage

Power Failures

A Current off for less than two minutes, no pressure change

B Current off for 13.6 hours, pressure decay from 800 to 621 kN/m^2 (116 to 90 Psia)

C Current off for 57.3 hours, pressure decay from 807 to 593 kN/m^2 (117 to 86 Psia)

TABLE 7 SFWEM ENDURANCE TEST OPERATING CONDITIONS

System (Water Compartment) Pressure, kN/m^2 (Psia)	517 to 2068 (75 to 300)
Module Temperature, K (F)	338.6 to 344.1 (150 to 160)
H_2-to-Water Pressure Differential, kN/m^2 (Psid)	13.8 to 20.7 (2 to 3)
O_2-to-H_2 Pressure Differential, kN/m^2 (Psid)	13.8 to 20.7 (2 to 3)
KOH Charge Concentration (Weight %)	25
Current Density, mA/cm^2 (ASF)	161 to 215 (150 to 200)

the range in operating conditions of the module during the testing. A total of 94 days (2256 hours) of endurance testing were accumulated during this phase of testing. Adding the shakedown and parametric test times to the endurance test time resulted in 111 days (2664 hours) of accumulated operation for the SFWEM and the STS.

Cell/Module Voltage. Figure 27 shows the variations in cell and module voltages as a function of current density for the 94 days of operation. The variation in module and maximum and minimum cell voltages during the first 440 hours of operation were a result of the manual variations in current density from 216 mA/cm^2 (200 ASF) during normal working hours to 107 mA/cm^2 (100 ASF) during the remainder of the time. These variations were performed to enable actual observation of module performance at higher current densities for extended periods of time to establish a current density level for the remainder of the endurance test.

The current density and resulting voltage spikes near 440 hours were caused by a capacitor malfunction in the current controller which resulted in a slowly increasing current density level from 108 mA/cm^2 (100 ASF) to 570 mA/cm^2 (530 ASF) over a period of about 20 hours.

Following replacement of the capacitor, cyclic current density operation was stopped and testing at a constant 161 mA/cm^2 (150 ASF) was continued for the remaining 1816 hours of the endurance test. During this time period the average voltage level was 1.65V, with an average spread of 50 mV between the lowest and the highest of the six voltages. A net rise of only 0.083 mV/cell/hour was observed during the first 200 hours of the constant current density operation, with basically constant average voltage observed for the remaining 1616 hours of testing. The average cell voltage of 1.65V observed during the constant 161 mA/cm^2 (150 ASF) operation bettered the design goal (1.70V at 161 mA/cm^2 (150 ASF)) by 50 mV/cell.

Degassing Requirements. The endurance test was started at a pressure of 1724 kN/m^2 (250 psia), based on the analytically projected value required to eliminate feed water cavity degassing. This pressure level, including several excursions to 2069 kN/m^2 (300 psia), was maintained for the first 440 hours of endurance testing. Periodic checks for the accumulation of gas in the cells' water feed cavities were performed using the GSU described earlier. No water feed cavity gas buildup was detected during this period. The average current density during this period of operation was 129 mA/cm^2 (120 ASF).

To identify the lowest practical pressure level where zero degassing requirements would exist, the operating pressure was lowered to 517 kN/m^2 (75 psia) and maintained at that level for a period of 1245 hours. The current density was set at 161 mA/cm^2 (150 ASF) based on the cyclic test results described above. Gas accumulation was observed for these conditions and the amounts were quantified. Typical results for a portion of this test are shown in Figure 28. Based on the data, approximately 0.0033 cm^3 of gas were liberated per gram of feed water

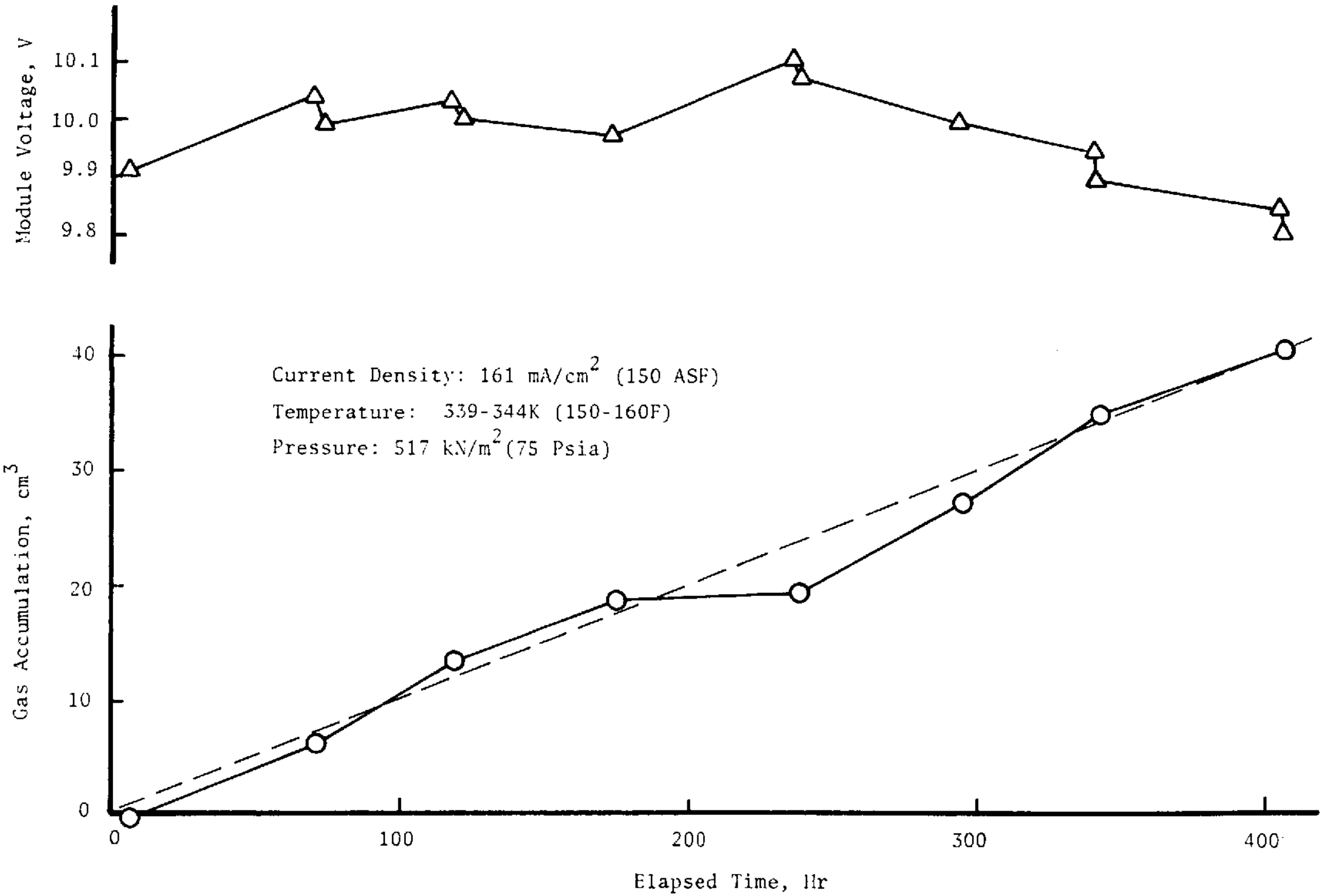


FIGURE 28 FEED WATER CAVITY GAS BUILDUP RATE

processed. This value compares to a solubility limit of about 0.0178 cm^3 air/gram water at the conditions of feed water addition. These results projected a lower than 1724 kN/m^2 (250 psia) pressure requirement to eliminate degassing. A pressure of 689 kN/m^2 (100 psia) was calculated to be sufficient to eliminate feed water cavity degassing requirements.

The SFWEM operating pressure level was increased to 807 kN/m^2 (117 psia) to allow for a margin of safety with respect to degassing and the system was operated at this level for the remaining 488 hours of the endurance test. No buildup of feed water cavity gas occurred.

Shutdowns. Table 6 summarizes the shutdowns experienced during the 94 days of operation. A total of seven system-related and three nonsystem-related (building power failures) shutdowns occurred. During a power loss shutdown, the STS does not depressurize the module nor does it reposition any valves, only the current is shut off. Upon return of power, the system can automatically continue operation by turning on current.

The longest totally uninterrupted operating span was 456 hours. The longest operation span without a system's related shutdown was 1426 hours (only interrupted by three building power failures, see Figure 27 and Table 6).

Component Evaluation Single Cell Tests

Single cell tests were performed as part of the total test program to evaluate various O_2-evolving electrodes, catalysts, and matrices. To allow simultaneous operation of the single cell and six-cell SFWEM, the single cell tests for the component evaluation were run on an available water electrolysis test stand. All tests were run to obtain a short-term comparison of alternate electrodes and matrices to those being used in the six-cell SFWEM.

Effect of Electrodes

Four different anode (O_2-evolving) electrodes were evaluated in the single cell testing. Of the four electrodes tested, one was the standard porous Ni electrode (Ni 004) used in the six-cell module, one was a titanium (Ti) electrode fabricated with an electrocatalyst identified under NASA sponsorship at Case Western Reserve University (CWRU) as being potentially capable of high current and low polarization (Ti 005), while the other two electrodes were Contractor-developed, LSI Ni 004A and Ni 005).

Figure 29 shows the internal resistance (IR) free voltage for current density spans for the four electrodes in the single cell. The three Contractor-developed NI electrodes exhibit relatively similar performance with the SFWEM baseline electrode yielding the lowest voltage. The Ti 005 electrode shows better performance, especially at higher current densities, (34 mV at 215 mA/cm^2 (200 ASF)) becoming a viable candidate as the future SFWEM baseline electrode. Its performance under long-duration testing remains to be demonstrated.

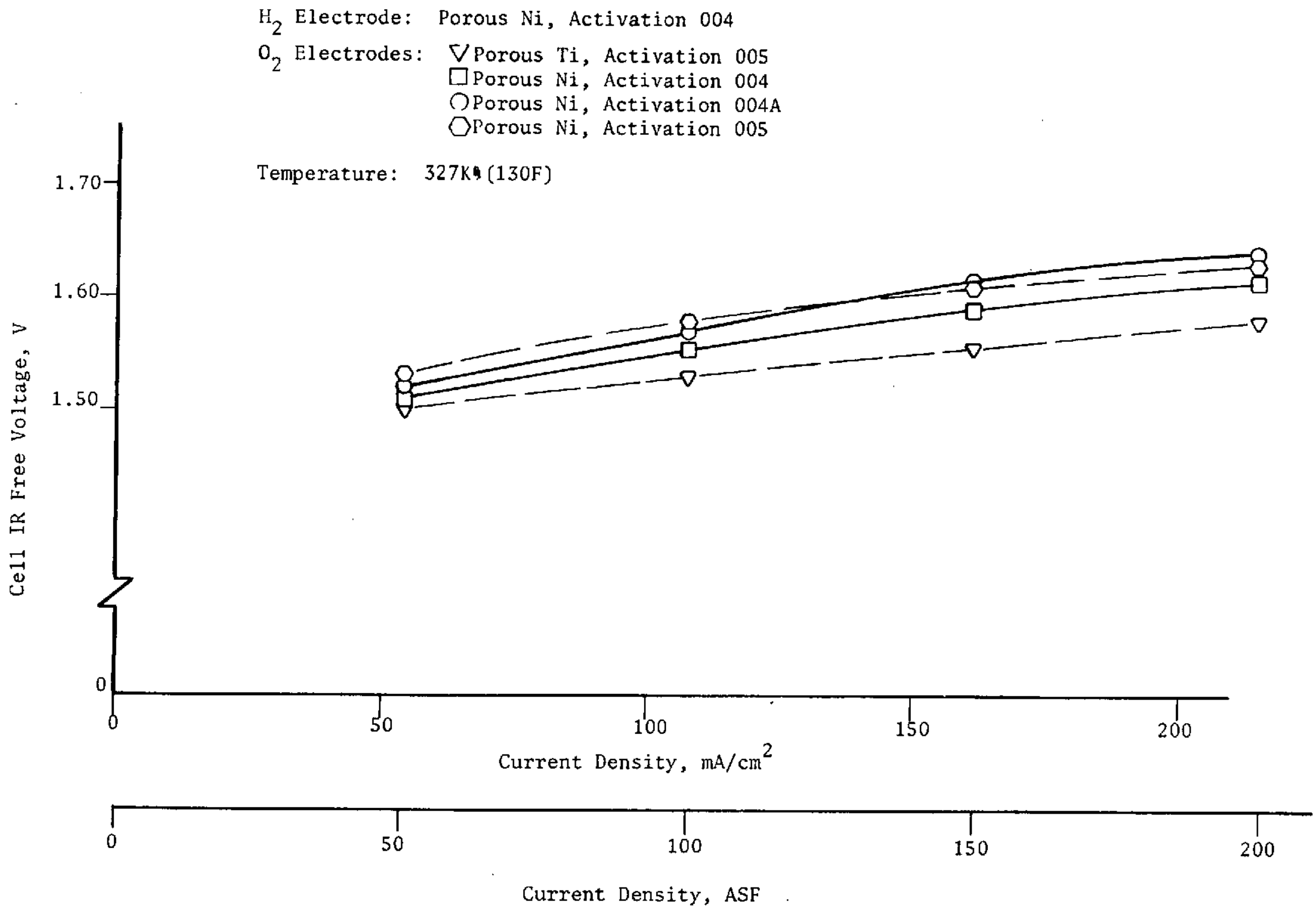


FIGURE 29 EFFECT OF VARIOUS O_2 ELECTRODES ON CELL VOLTAGE

Effect of Matrices

The cell matrix used in the SFWEM consists of reconstituted asbestos. This type of matrix yields good performance, however, its operating temperature must remain below 355K (180F) for long-term operation because KOH reacts with the asbestos fiber material. This restriction on temperature prevents the decrease in power possible by operating at elevated temperatures. A more KOH-resistant matrix material is desirable.

Two matrix materials were tested in the single cell. Figure 30 shows the cell terminal voltage obtained as a function of current density. Composition C is made from a material considered to be resistant to KOH at temperatures up to 445K (340F). The figure shows that Composition C produces a lower terminal voltage throughout the operating range reaching a 58 mV difference at 215 mA/cm^2 (200 ASF).

While Composition C exhibits high temperature properties and slightly better performance than the baseline matrix, its bubble pressure, when supported by the porous Ni plaque electrodes, is less than the baseline matrix although capable of a 68.9 kN/m^2 (10 psi) differential.

DEHUMIDIFIER MODULE

Dehumidification of product gases from water electrolysis systems is necessary when the exhaust gases have a dew point greater than the maximum allowable dew point level within the cabin or greater than the dry bulb temperature of the media through which the plumbing passes. Normally, this level is 287K (57F) which is equivalent to a water vapor partial pressure of 1.6 kN/m^2 (12 mm Hg). Various methods are available to remove water vapor from the product gases. Four practical approaches are:

1. Utilization of condenser/separators.

2. Operation of the electrolysis system at a sufficiently high pressure level to insure that after expansion of the product gases the partial water vapor pressure will be less than the maximum allowable of 1.6 kN/m^2 (12 mm Hg).

3. The addition of an electrochemical Dehumidifier Module (DM) in the product gas lines.

4. A combination of two or more of the above.

The DM concept uses water vapor electrolysis to remove the water vapor carried with the product gases. The O_2 and H_2 from the main electrolysis module are passed respectively through the anode and cathode cavities of the water vapor electrolysis cells of the DM. The affinity for moisture of the DM's electrolyte causes the water vapor to be transferred into the cell where, as a result of an imposed current, the water is electrolyzed to form additional O_2 and H_2.

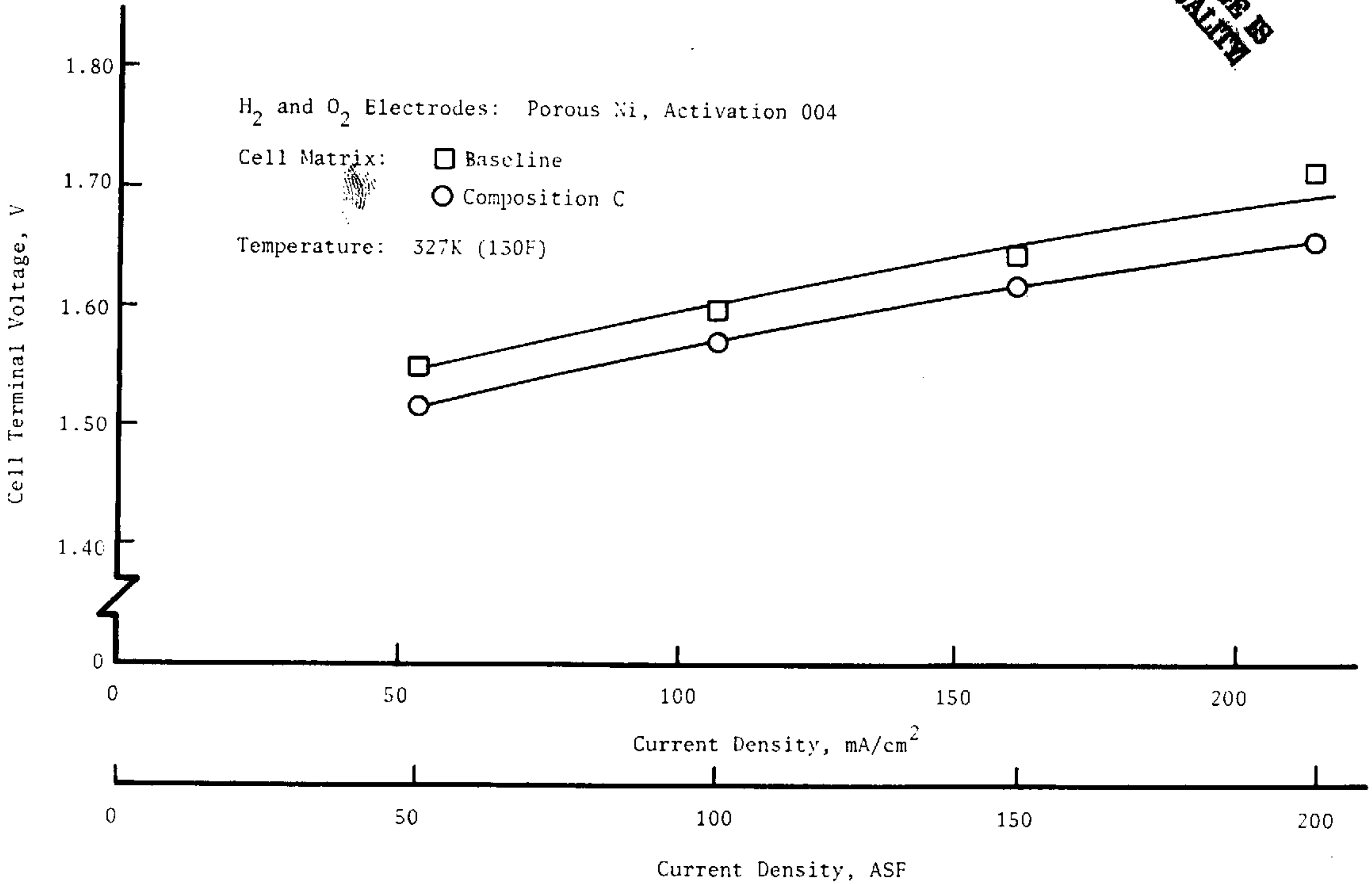


FIGURE 30 EFFECT OF CELL MATRIX ON TERMINAL VOLTAGE

One advantage of the DM is the almost total utilization of water processed by the main electrolysis system, including that normally lost through humidification of the product O_2 and H_2. By operating the electrolytic dehumidifier upstream of any system pressure regulators, trace heating of lines and regulators, which are electrical power consumers, is eliminated. Also, the electrolytic method eliminates condenser/separators required by all other low pressure water electrolysis systems where expansion alone of product gases does not achieve the minimum allowable partial water vapor pressure.

Design Specifications

The detailed design specifications to which the DM was designed are listed in Table 8. The DM was sized to dehumidify the product gases of a one-man, capacity O_2 generating system allowing it to readily interface with the one-man capacity SFWEM. The amount of water carried in the product gases of the SFWEM is a function of its operating pressure. The lower the pressure, the greater the amount of water and, therefore, the greater the capacity required for the DM. A minimum pressure level of 345 kN/m^2 (50 psia) was selected and used to size the one-man capacity DM.

The capacity of the SFWEM is expressed in O_2 production per unit time. The amount of water carried by both product gases is therefore best calculated and expressed as a function of O_2 production rate and the specific humidity of the exhaust O_2 gas only. The resulting formula shows that the total amount of water carried out by the SFWEM as humidity is equal to three times the O_2 production rate times the specific humidity of the product O_2. Based on these calculations, the number of cells required for the DM is readily calculated and expressed as the function of O_2 operating pressure for a given electrolyte charge concentration and operating temperature. Table 9 shows O_2 operating pressure, specific humidity of the product O_2, and the number of cells required for the DM at both 50 and 30 A/ft^2.

Three cells were selected for the DM to allow operation at O_2 pressures down to 50 psia with the SFWEM at a design capacity of 0.907 kg/d (2.0 lb/day) of O_2. At the design pressure of 1724 kN/m_2 (250 psia) the DM is capable of dehumidifying the product gases from a four- to five-man O_2 generating system.

Process Description

The major process occurring within the DM is the electrochemical decomposition of water. This process occurs within the electrode-cell matrix-electrode composite. The oxidation reaction in an acid system is

$$2H_2O = O_2 + 4H^+ + 4e^- \qquad (9)$$

The reduction reaction is

$$2H^+ + 2e^- = H_2 \qquad (10)$$

TABLE 8 DM DESIGN CHARACTERISTICS

O_2 Dehumification Rate, g/s (Lb/Day)[a]	0 to 0.016 (3.0)
H_2 Dehumidification Rate, g/s (Lb/Day)[a]	0 to 0.002 (0.378)
Operating Pressure Range, kN/m^2 (Psia)	103 to 1724 (15 to 250)
O_2 to H_2 ΔP, kN/m^2 (Psid)	0 to 34.5 (0 to 5)
Operating Temperature Range, K(F)	Ambient to 338.6K (150F)
Voltage at 54 mA/cm^2 (50 ASF), V	1.9
Current Density Range, mA/cm^2 (ASF)	0 to 54 (50)
Water Consumption at 4A/cell, g/s (Lb/Day)	0.00047 (0.089)
Number of Cells	3
Active Area per Cell, cm^2 (Ft^2)	92.9 (0.1)
Volume, m^3 (Ft^3)	0.00688 (0.24)
Basic Configuration, cm (In)	8.89 x 25.4 x 30.48 (3.5 x 10 x 12)
Electrolyte Concentration, % H_2SO_4 w/w	51
Heat Removal Mechanism	Liquid Coolant
Water Feed Mechanism	Absorption from O_2 and H_2 inlet gases
Gravity, G	0 to 1
Duty Cycle	Continuous and cyclic

(a) The DM shall dehumidify to a 287K (57F) dew point while operating at 103 to 1724 kN/m^2 (15 to 250 Psia).

TABLE 9 NUMBER OF CELLS FOR DM

P_{O_2}, kN/m^2	Psia	γO_2,[a] kg Water/kg O_2	Number of Cells in Dryer at 54 mA/cm^2 (50 ASF)	32 mA/cm^2 (30 ASF)
101	14.7	0.170	11.50	19.20
207	30.0	0.076	5.10	8.50
345	50.0	0.046	3.10	5.20
552	80.0	0.025	1.70	2.80
690	100.0	0.020	1.35	2.25
1034	150.0	0.013	0.88	1.47
1379	200.0	0.010	0.66	1.10
1724	250.0	0.008	0.57	0.95

(a) kg of water/kg of O_2 for 352K (175F) and 35% KOH.

resulting in the overall net reaction of

$$\text{electrical energy} + H_2O = H_2 + \tfrac{1}{2}O_2 + \text{heat} \tag{11}$$

Electrolysis Concepts Selected

In concept, the DM is a water electrolysis module with water supplied in vapor form with the H_2 and O_2 obtained from the SFWEM. The design of the DM, as in any water electrolysis module, requires the definition of four basic concepts. They are:

1. The nature of the electrolyte
2. Electrolyte incorporation
3. Heat removal
4. Water addition

Electrolyte

A sulfuric acid (H_2SO_4) electrolyte was selected for the DM because of its affinity to absorb water from gases with higher water vapor pressure. Sulfuric acid also will not dry out and crystallize at high concentrations, allowing, therefore, operation at the low dew points desired.

Electrolyte Incorporation

The electrolyte incorporation selected was that of using a porous matrix made from custom-blended acid resistant asbestos to (1) keep the cell electrodes close together for low internal resistance, hence low equivalent weight and low power consumption requirements, and (2) provide a high stability to pressure differentials.

Water Feed

By definition, the water feed to the electrolysis site will be in the form of vapor carried in the O_2 and H_2 gases at the SFWEM operating pressure, electrolyte concentration, and temperature. The absorbed water is then electrochemically decomposed into O_2 and H_2 and, because of the direction of electron flow, is placed back into its respective H_2 and O_2 cavities as a gas.

Heat Removal

A liquid coolant loop circulating through a separate cavity within each cell of the DM was selected to simplify eventual integration with the SFWEM. Since near equal temperatures for the DM and the SFWEM are desired to eliminate premature condensation in the DM's inlet manifolds and ports, a common liquid coolant loop results in minimum components and controls.

DM Hardware Design and Operation

The basic cell design used for the SFWEM was adapted to the design of the DM. The injection molded polysulfone cell parts, being compatible with the acidic environment were directly applicable. Materials changes in the remaining cell components were, however, required. Also, a reduction from the four process fluid cavities to three (no feed water cavity) was necessary.

The resulting cell cross-section schematic is shown in Figure 31. Critical components of the cell are the cell matrix and electrodes where water decomposition takes place. The cell matrix, Item 2, is the area where the H_2SO_4 electrolyte is retained. It is supported on the O_2 side by a porous TI anode (Item 3) and on the H_2 side by a screen electrode (Item 1). Hydrogen comes into the H_2 cavity (Item 4) which is created by Ti expanded metal. Water vapor is absorbed by the H_2SO_4 contained in the electrode where it is electrolytically decomposed by the current passing through the cell. The H_2 evolved goes back in the H_2 cavity and is carried out into the H_2 manifold. A similar process occurs in cavity five where saturated O_2 comes in, relinquishes its water to the cell matrix and dry O_2 is evolved back into the O_2 cavity where it is collected in the O_2 outlet manifold. Shown also in the schematic is the bipolar connection with the current flow indicated. Three of these single cells are sandwiched in between polysulfone insulation plates. The insulation plates are then retained by stainless steel endplates.

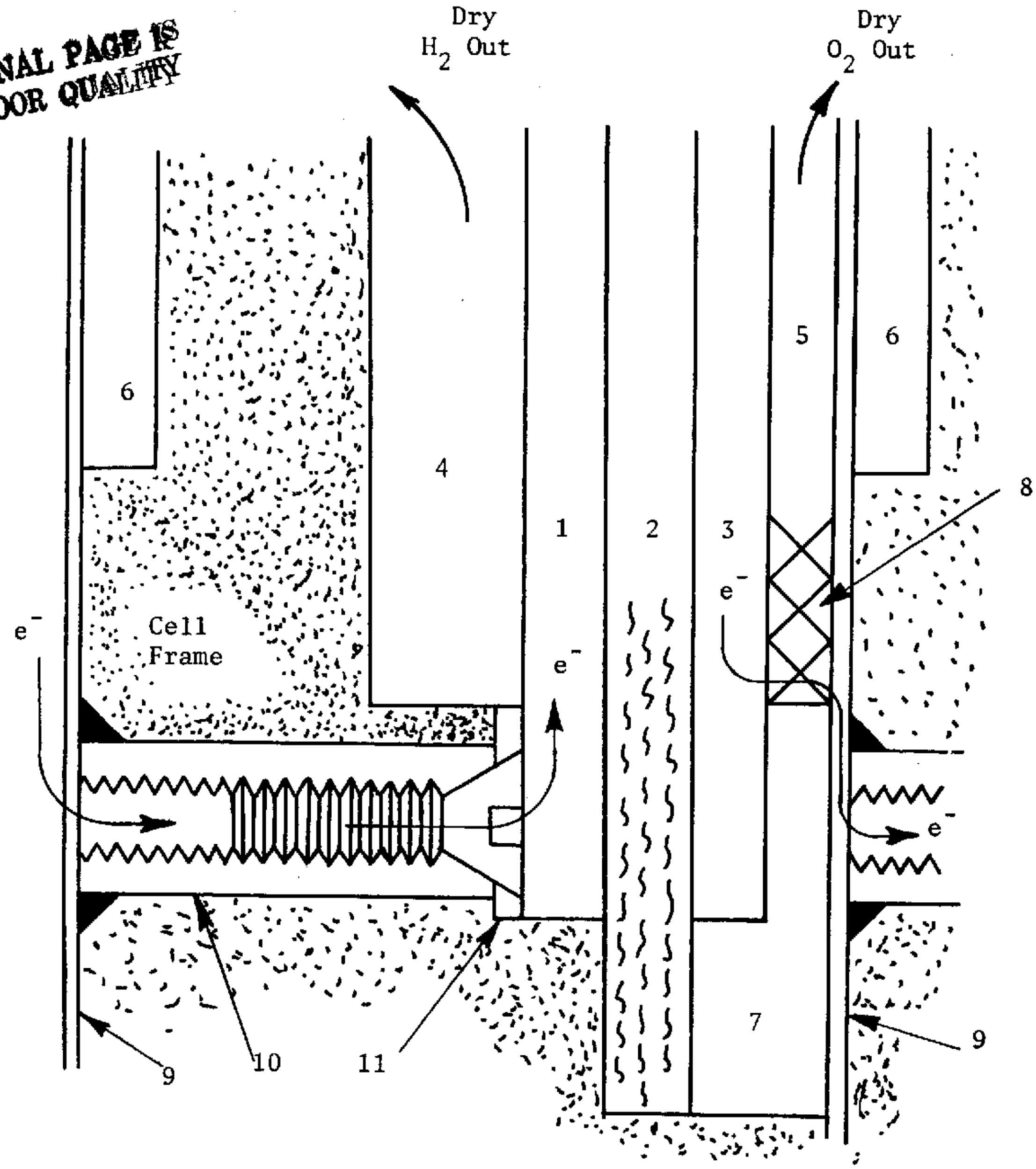
Dehumidifier Capacity

The DM was designed to reduce the dew point of the product gases from the SFWEM to less than 287K (57F), which is considered maximum for a spacecraft atmosphere. To meet this requirement, the DM must be operated at the proper current level to electrolyze the incoming water vapor contained in the product H_2 and O_2. If the SFWEM generates 0.907 kg (2 lb) of O_2/day, then, stoichiometrically, 0.1134 kg (0.25 lb) of H_2 are generated. Since the generation rates and approximate humidity ratios of the gases are known, the amount of water that must be electrolyzed can be calculated and the required DM current can be determined.

DM GROUND SUPPORT ACCESSORIES

The schematic for the GSA designed for testing the DM is shown in Figure 32. The function of the GSA is to simulate the H_2 and O_2 exhaust gas streams from the SFWEM while the DM is being tested independently.

As shown in Figure 32, bottled H_2 and O_2 are fed into the system and bubbled through humidifiers (H1 and H2). The dew points of the gases are controlled to the desired level by adjusting the humidifier water temperatures. Provisions are available to bypass the humidifiers so that the water supply may be replenished (HV7-HV10). The gases then flow past temperature sensors (TC1 and TC2) and dew point sampling ports into the DM. The H_2 enters the cathode cavity and the O_2 enters the anode cavity. The O_2 generated at the anode mixes with O_2 in the anode cavity and the H_2 generated at the cathode mixes with the H_2 in the cathode cavity. The gases flow past pressure sensors (PG3 and PG4), temperature sensors



1. Screen Cathode
2. Blue Asbestos Matrix
3. Porous Ti Anode
4. H_2 Cavity
5. O_2 Cavity
6. Coolant
7. Compression Frame
8. Expanded Titanium
9. Ti Current Collector
10. Ti Current Stub
11. Cathode Current Collector

FIGURE 31 DM CELL CROSS SECTION SCHEMATIC

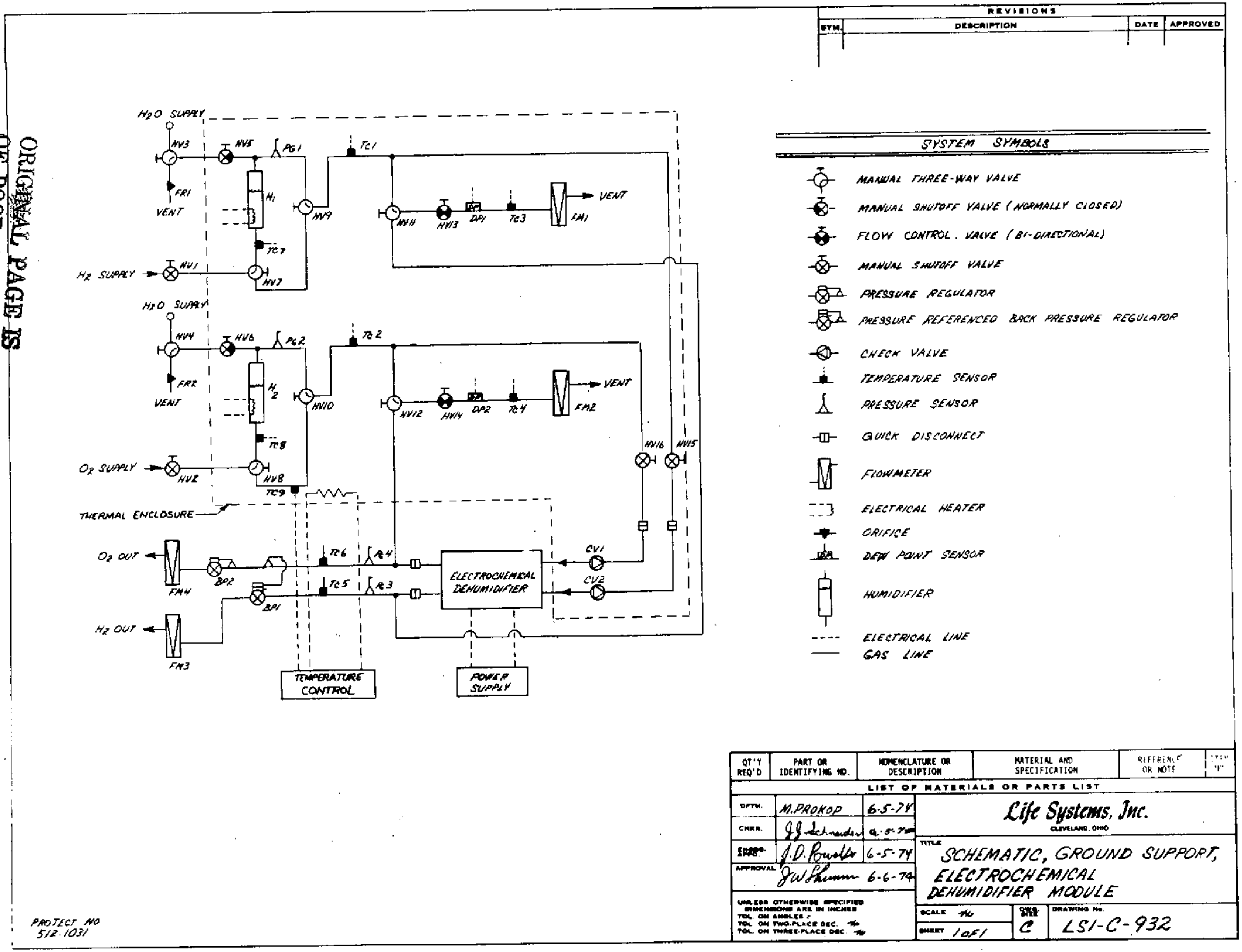


FIGURE 32 DM GROUND SUPPORT SCHEMATIC

(TC3 and TC4), and dew point sampling ports. The O_2 pressure is controlled by a backpressure regulator (BP2) and the H_2 pressure is controlled by a dome-loaded backpressure regulator (BP1) referenced by the O_2 steam pressure. The gas flow rates are measured downstream of the regulators by soap bubble flowmeters.

To prevent excessive dehydration of the DM it must be operated with a constant voltage/constant current automatic crossover power supply. The current will remain constant at the set value (between 3 and 5A) until the DM voltage reaches the set value (between 6 and 6.6 volts, i.e., 2 to 2.2 volts per cell). The current will then drop to keep the voltage at the set value. This method of operation assures that all water removed from the gases by the electrolyte is electrolyzed. Figure 33 is a photograph of the GSA with the DM in place. All the lines carrying moist gases were covered with insulation to prevent condensation, but have been left out of the photograph for clarity. All O_2 lines and components in the system were cleaned for 2069 to 3448 kN/m^2 (300 to 500 psia) O_2 service. The test stand is complete with its own dew point sensors, humidifiers with heaters, separate H_2 and O_2 pressure test gauges, and thermocouple temperature sensors.

DEHUMIDIFIER MODULE TESTING

Following fabrication of the DM and its test system the DM was charged with 51% w/w H_2SO_4 and installed in its test system. Preliminary performance evaluation tests were then performed. Figure 34 shows a voltage current characteristic for the DM cells obtained during its initial operation.

The DM was operated for a total of 72 hours, including 10 hours of integrated operation with the SFWEM. Figure 35 shows the DM average cell voltage during this testing. At one point early in the testing, measurements were made of DM O_2 inlet flow, O_2 outlet flow, and current. Based on these measurements the module was producing 98% of the theoretical O_2 flow. Dew point measurements of inlet and outlet gases have also shown that the DM was functioning as planned. During the shakedown tests, a measurement showed that the inlet dew point of 295K (72F) was being reduced to 283K (50F). These tests have been limited in duration. More extensive parametric endurance and integrated testing is needed.

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions are a result of this development program:

1. The advanced SFWEM can be operated without water feed cavity degassing. This was demonstrated for 440 hours at 129 mA/cm^2 (120 ASF) and 1724 kN/m^2 (250 psia) and for 488 hours at 161 mA/cm^2 (150 ASF) and 807 kN/m^2 (117 psia) during the endurance test.

2. The advanced SFWEM can be operated for 94 days as was shown by the successful endurance test performed.

3. Control and monitor instrumentation can be designed for the SFWEM to provide fail-safe automatic unattended operation as was demonstrated by the instrumentation designed and used for SFWEM testing.

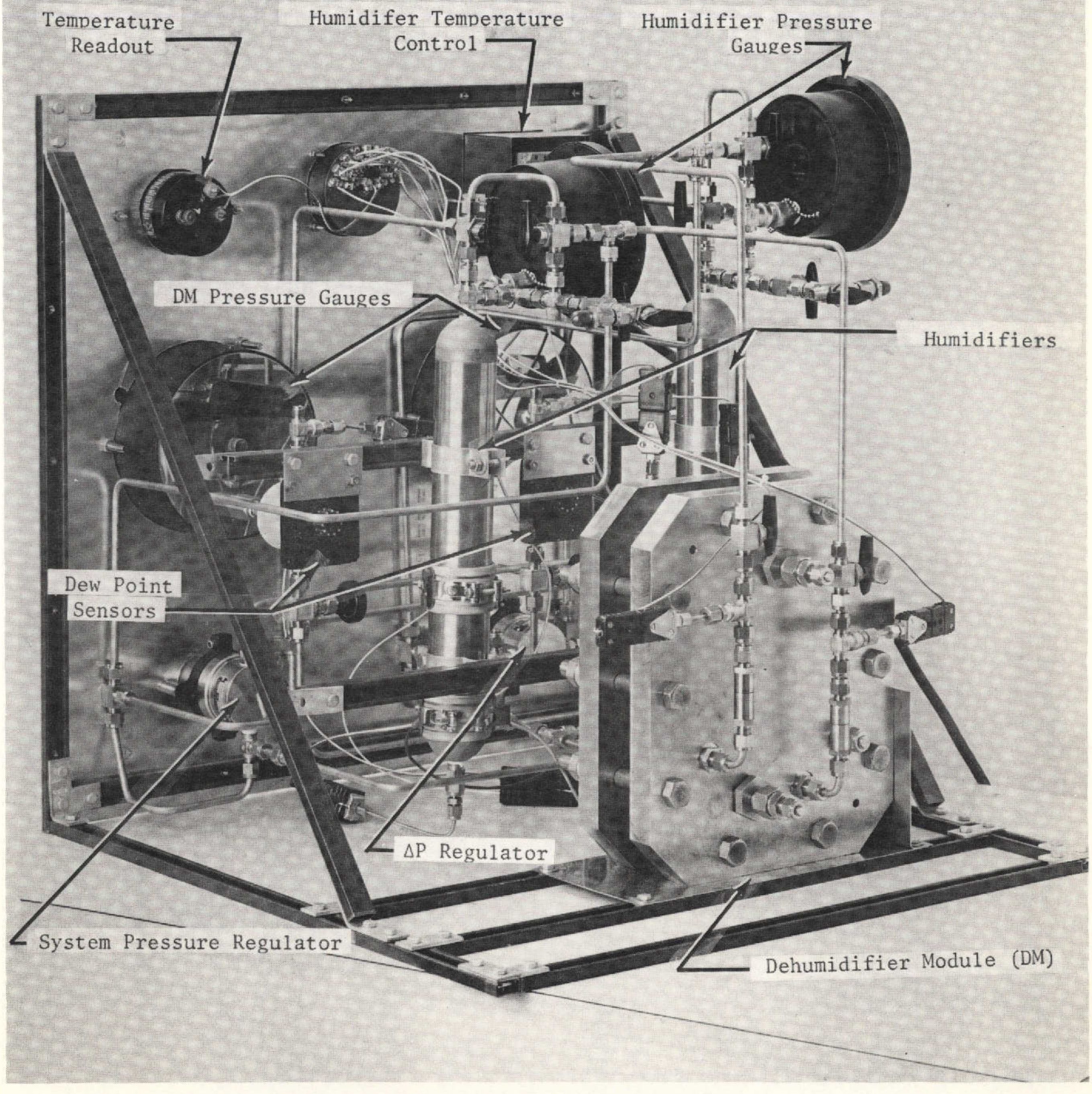


FIGURE 33 DEHUMIDIFIER MODULE AND TEST SYSTEM

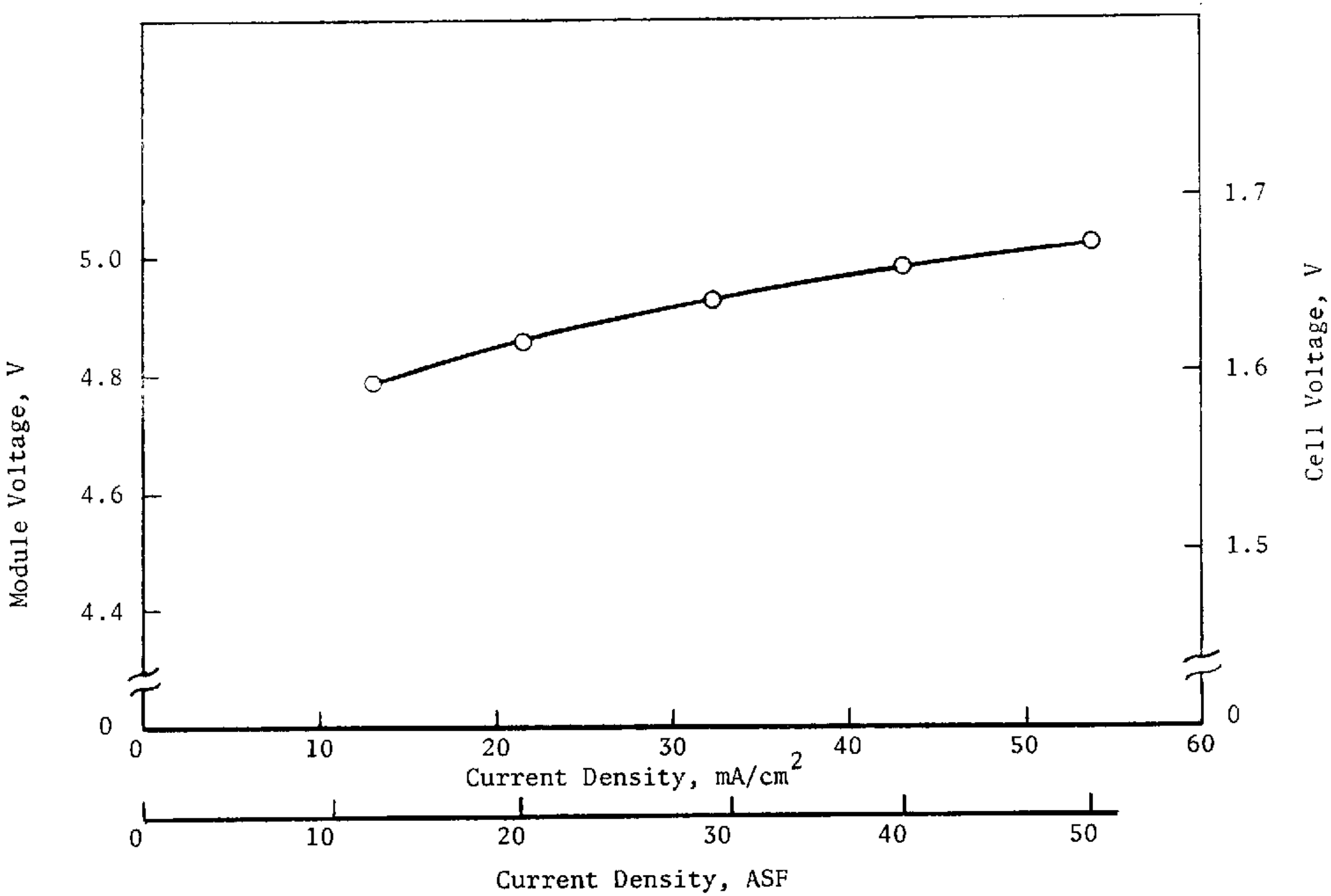


FIGURE 34 DM VOLTAGE VERSUS CURRENT

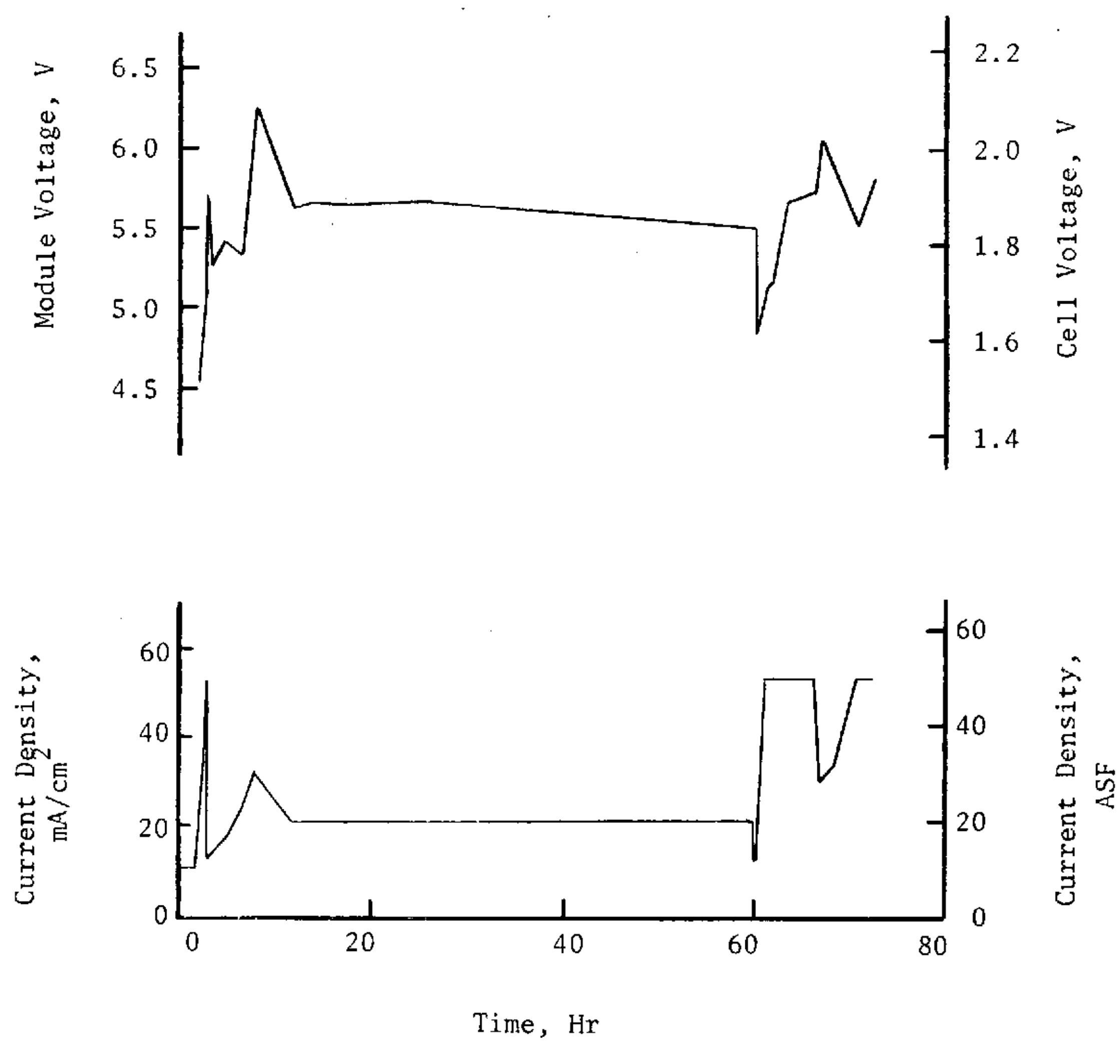


FIGURE 35 DM CELL VOLTAGE AND CURRENT DENSITY VERSUS TIME

4. Short-term testing has shown that cell voltage can be reduced by using a different electrode catalyst and cell matrix. A catalyst which was tested for 100 hours produced a 34 mV lower cell voltage at 215 mA/cm^2 (100 ASF). A cell matrix which was tested for 100 hours produced a 58 mV lower cell voltage at 215 mA/cm^2 (200 ASF) and has better high temperatures characteristic than the standard matrix. Higher temperature will further reduce cell voltage.

5. The SFWEM can be operated with liquid cooling and better performance obtained. This was demonstrated on the program's endurance test with the narrow cell voltage distribution of ±25 mV for more than 1800 hours.

6. A single SFWEM cell can be run at current densities up to 1076 mA/cm^2 (1000 ASF) for short periods as was demonstrated during the SFWEM single cell DVTs.

7. The SFWEM can be operated at pressures up to 1724 kN/m^2 (250 psia) as was demonstrated during parametric and endurance tests. The voltage increases at a rate of 0.6 mV per kN/m^2 (4.1 mV per psia) over the range 690 to 1725 (100 to 250 psia) at 215 mA/cm^2 (200 ASF) and approximately 342K (155F).

8. The SFWEM demonstrated a 2.6 mV/K (1.4 mV/F) decrease in cell voltage over the range of 108 to 538 mA/cm^2 (100 to 500 ASF), and 101 to 207 kN/m^2 (14.7 to 30 psia), and 316 to 366K (110 to 200F).

9. Operation under a typical near-earth orbit duty cycle was successful and can result in a projected weight savings of 185Kg (405 lb) for a six-man O_2 Generating Subsystem, assuming a 122 kg/kw (270 lb/kw) power penalty for the cyclic mode and 268 kg/kw (590 lb/kw) for continuous regulated DC power source.

10. The feed water supply tank can be automatically refilled from a 207 kN/m^2 (30 psia) water supply while the SFWEM was operating at 1724 kN/m^2 (250 psia). This automatic water tank filling was controlled by automatic circuits in the control instrumentation and was demonstrated during the endurance test.

11. A DM can be used to remove moisture from the SFWEM product gases, eliminating the need for condenser/separator and converting nearly all of the water to product gases. This was demonstrated during short-term integrated SFWEM-DM tests.

The following recommendations are a result of this development program:

1. Operation of a single cell at current densities up to 1076 mA/cm^2 (1000 ASF) was demonstrated. The limiting factor in the SFWEM is the current collection components. The SFWEM should be modified to allow operations at current densities up to 1076 mA/cm^2 (1000 ASF). This modification would require redesign of the current collectors, intercell and intracell current flow paths.

2. The SFWEM should be subjected to a series of parametric tests to show that the current collection modifications have accomplished the desired results. These tests would include current density spans up to 1076 mA/cm^2 (1000 ASF), pressure variations up to 1724 kN/m^2 (250 psia), and temperatures up to 366K (200F).

3. Long-term operation of SFWEM at current densities of 1076 mA/cm^2 (1000 ASF) should be accomplished. Endurance testing would assure that the SFWEM's performance at high current densities is stable.

4. Extended integrated testing (30 days or more) of the DM with the SFWEM should be completed. This test is required to completely evaluate the compatibility of the two modules, to evaluate long-term performance, and to obtain data needed to allow the design of an integrated SFWEM-DM module.

5. The O_2 electrode identified in short-term testing as being superior to the SFWEM baselines should be subjected to a series of complete parametric and endurance tests, especially the latter. The use of these electrodes would result in a savings of 26 watts in a six-man system which at 122 kg/kw (270 lb/kw) would save 3.2 kg (7.0 lb) in power source weight.

6. The matrix identified in short-term tests as being better than the SFWEM baseline matrix should be subjected to a complete series of parametric and endurance tests, especially the latter. The use of this matrix would result in a savings of 44 watts in a six-man system which at 122 kg/kw (270 lb/kw) would save 5.4 kg (11.8 lb) in power source weight at present operating temperatures. The new matrix would allow higher SFWEM operating temperatures which would also result in additional lower cell voltages and additional equivalent weight savings.

7. The SFWEM should be increased in size to a four- to six-man level to allow integration and testing with Air Revitalization Systems sized at four- to six-man levels.

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APPENDIX 1 MODE TRANSITION SEQUENCES

Power On Sequence

1. Close circuit breaker to system.
2. Power on reset circuit sends the system to the SHUTDOWN mode.
3. All monitor and control circuits are powered and operating normally except the current is off and the liquid coolant pump is off. The system is in the SHUTDOWN mode.

Startup Sequence

1. Operate ON pushbutton.
2. Coolant pump is turned on and a water tank filled cycle (see below) is initiated.
3. At the completion of the fill cycle, the system is in the ON mode. The module has current and the coolant pump is operating.
4. As the module reaches operating temperature, the temperature control system operates three-way solenoid valve SV10 to maintain its temperature.[a]
5. No further action occurs until about six hours have elapsed at which time a water tank fill cycle will again be initiated.

Water Tank Fill Cycle Sequence

1. Fill cycle is initiated by automatic internal time approximately every six hours or whenever the system is turned on.
2. Hold all monitor printed circuit (PC) cards reset which prevents temporary low cell voltages and pressure differentials from causing a shutdown during the fill cycle.
3. Reduce the module current to a preset value (set by PC card adjustment, presently 2.5 amp).
4. Energize the normally open solenoid valve SV8 which isolates the water tank from the water feed cavities in the module.
5. Energize the three-way solenoid valve SV7 to allow the pressure in the O_2 side of the water tank to bleed out rapidly through the check valve.

(a) Refer to Figure 15 for location of all valves.

6. A delay of 10 to 15 seconds is allowed for this pressure bleeding to occur.

7. Energize the normally closed solenoid valve SV9 which allows the process water to flow into the water tank.

8. When the water tank becomes full, a large change in pressure as measured by pressure transducer DP3 will occur. When this signal is received, solenoid valve SV9 is de-energized which stops the process water flow.

9. De-energize solenoid valve SV7 which allows the O_2 side of the water tank to be slowly repressurized through the restrictor in parallel with the check valve.

10. A delay of 10 to 15 seconds is allowed for this repressurization to occur.

11. De-energize solenoid valve SV8 which allows water to again flow to the module water feed cavity.

12. Return the module current to the original value as set by the front panel control.

13. Two minutes later remove the automatic reset on all monitor PC cards.

14. The six-hour timer is reset and a new time period started.

Shutdown Sequence

1. Either operating the manual SHUTDOWN pushbutton or receiving a malfunction signal from the monitor circuits will initiate a shutdown sequence.

2. If a fill cycle is in progress, the cycle will be allowed to be completed as described above, except Steps 12, 13, and 14 will not be executed. If it was not in a fill cycle, the current is turned off and the fill cycle timer is disabled.

3. The coolant pump is turned off.

4. Solenoid valve SV4 is opened. This allows the water (system) pressure to drop slowly to atmospheric through a check valve.

5. When the water pressure reaches about 1 psi above atmospheric, solenoid valves SV3, SV5, and SV6 are opened. This initiates a N_2 purge of the O_2 and H_2 cavities in the module.

6. Wait two minutes for the N_2 purge to be accomplished.

7. The N_2 solenoid valves SV5 and SV6 are closed. This stops the N_2 purge. At the same time solenoid valves SV1 and SV2 are opened. This allows the O_2 and H_2 compartments in the module to drop to atmospheric pressure.

8. Wait 10 to 15 seconds for these pressures to stabilize.

9. Solenoid valves SV1, SV2, SV3, SV4, SV5, and SV6 are closed. This isolates the module and completes the shutdown sequence.